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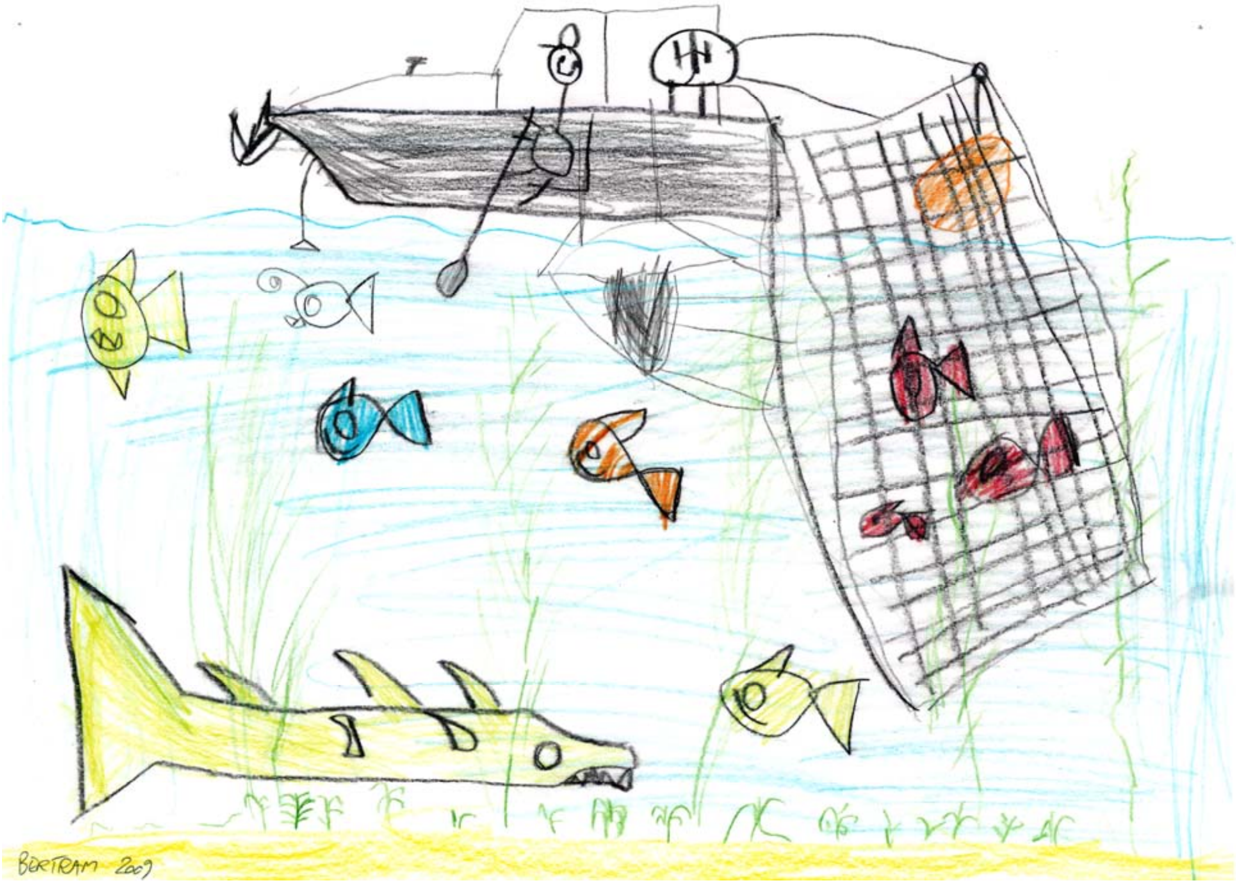

Section of Environmental Engineering
Aalborg University
Ph.D. thesis, 2010

Reduction of discards in the Danish *Nephrops* (*Nephrops norvegicus*) directed trawl fisheries in Kattegat and Skagerrak

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Ph.D. thesis, 2010
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Preface

The present thesis is submitted in partial fulfillment of the requirements for obtaining the Doctor of Philosophy (Ph.D.) degree. The thesis consists of a review and four supporting papers. Three papers are published and one is ready to be submitted for publication.

I wish to express my sincere thanks to my supervisors: Dr. Niels Madsen and Dr. Bent Herrmann from the Technical University of Denmark – National Institute of Aquatic Resources (DTU Aqua) and Associate Professor Dr. Jens-Ole Frier, Aalborg University who all helped keeping me on track.

Further I wish to thank:

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- Jens V. Poulsen and Henning H. Jensen, the skippers of *Canopus FN234* and *Mette Amalie RS30,* for much good advice and valuable knowledge on the distribution of species and sizes
- The co-authors of the papers and Bo Lundgren (DTU Aqua) for fruitful discussions that greatly improved the manuscripts
- Kurt Hansen (SINTEF) and Lars Peter Jensen (Strandby Net) for help with transforming ideas into new gear designs
- My wonderful family for not kicking me out of the tribe

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Hirtshals, October 2010

Rikke Petri Frandsen

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Paper II: Frandsen, R.P., Herrmann, B., Madsen, N., 2010. A simulation-based attempt to quantify the morphological component of size selection of Nephrops norvegicus in trawl codends. Fisheries Research 101, 156-167.

Paper III: Frandsen, R.P., Madsen, N., Krag, L.A., 2010. Selectivity and escapement behaviour of five commercial fishery species in standard square- and diamond-mesh codends. ICES Journal of Marine Science. *IN PRESS*. DOI: 10.1093/icesjms/fsq050.

Paper IV: Frandsen, R.P., Herrmann, B., Krag, L.A., Madsen, N., 2010. Improving size selectivity of *Nephrops* (*Nephrops norvegicus*) in a multi-species fishery by use of square mesh bottom panels. Will be submitted to Fisheries Research.

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Dansk resumé (abstract in Danish)

Det danske fiskeri efter jomfruhummer foregår med trawl og bifangster af både rundfisk og fladfisk udgør en vigtig del af økonomien i fiskeriet. De anvendte trawl er derfor udviklet til at tilbageholde både de relativt små hummer og de større fisk. Konsekvensen af dette design er at redskabet også tilbageholder et stort antal fisk og jomfruhummer der ikke må landes fordi de er mindre end det gældende mindstemål. Den del af fangsten, der af den ene eller anden grund ikke skal landes, bliver smidt over bord - dette refereres til som discard. Da størstedelen af discarden dør, udgør den både et økonomisk, økologisk og politisk problem. Denne Ph.D. består af en sammenfatning og 4 artikler, der dels beskriver problemstillingen og dels fremlægger redskabsteknologiske løsninger der kan mindske discarden.

Det studie der ligger til grund for Artikel I bestod i en undersøgelse af de selektive egenskaber de redskaber der primært bruges i fiskeriet. De havde tidligere været undersøgt, men for mange arter var der ikke estimeret de selektionsparametre, der bruges til at sammenligne forskellige redskabers længdebaserede tilbageholdelse af de forskellige arter. Forsøget dokumenterede at den relativt høje discard i fiskeriet primært skyldes at reguleringer på mindstemål og maskestørrelser ikke harmonerer. Mekanismerne bag størrelsesselektionen af fisk er veldokumenteret, men pga. jomfruhummers irregulære morfologi og ringe svømmeevne, er selektionen af denne art blevet betragtet som mindre forudsigelig og derfor uregulerbar. Artikel II præsenterer resultaterne fra en omfangsrig opmåling af de dele af jomfruhummeren, der har betydning for om den kan slippe gennem en maske eller ej. Efterfølgende simuleringer demonstrerede dels at selektionsprocessen for jomfruhummer er forudsigelig og dels at det i høj grad er variation i maskegeometrien der bestemmer hvor effektiv størrelsesselektionen af et redskab er for denne art. Et andet vigtigt resultat af disse simuleringsforsøg var en klar indikation af at jomfruhummer slipper ud gennem masker i hele fangstposens længde. Dette er i modsætning til fisk, der primært undslipper redskabet i den allerbagerste del af fangstposen. Maskerne i fangstposen i langt størstedelen af trawlfiskerierne er diamantformede og efterhånden som redskabet fyldes med fangst vil det øgede træk lukke maskerne. Dette sker ikke i kvadratmasker og disse har ofte bedre selektive egenskaber for en række arter deriblandt jomfruhummer og rundfisk (fx torsk), mens nogle arter af fladfisk har

lettere ved at slippe gennem diamantmasker. Hvis størrelsesselektionen af flere forskellige arter skal tilgodeses, kan det derfor være en mulighed at kombinere forskellige masketyper. Den optimale placering af de enkelte masketyper vil afhænge af i hvilken retning de forskellige arter primært søger at slippe ud. I Artikel III er beskrevet et forsøg hvor fisk og jomfruhummer, der slap ud gennem maskerne i hhv. det øvre og det nedre panel, blev opsamlet i forskellige opsamlingsposer. Baseret på viden indhentet i dette og de foregående forsøg blev der konstrueret en fangstpose hvor det nederste panel var lavet af kvadratmasker mens de øvrige paneler var lavet af diamantmasker. For jomfruhummer og torsk havde denne kombinerede fangstpose ligeså god størrelsesselektion som en fangstpose lavet alene af kvadratmasker mens størrelsesselektionen af rødspætte tilsvarende den i en ren diamantmaske fangstpose. Resultaterne fra dette forsøg er præsenteret i Artikel IV.

Implementering af mere selektive redskaber samt forvaltningsmæssige tiltag der fokuserer på de reelle fangster i stedet for landingerne vil bidrage til udviklingen af et mere selektivt fiskeri. I den følgende sammenskrivning præsenteres in række reskabsteknologiske tiltag, der gør det muligt at forbedre selektionen i jomfruhummerfiskeriet.

Abstract

The Danish *Nephrops* directed fishery is conducted with trawl and by-catch of roundfish as well as flatfish constitute an important part of the revenue. The trawls are therefore designed to retain both the relatively small *Nephrops* and the larger fish. Consequently, the gear also retains large amounts of fish and *Nephrops* below the minimum landing size. The fraction of the catch that for one reason or another is not landed will be thrown over board – this is referred to as discard. The majority of the discard will die and it therefore poses an economical, ecological and political problem. The present Ph.D. thesis consists of a review and 4 papers, describing the problem and proposing technological measures that reduce discards.

The study on which Paper I is based was an investigation of the selective properties of the fishing gears used in the fishery. The gears had been investigated previously but selection parameters that are used for comparing the length-based retention still needed to be estimated for several species. The investigation documented that the relatively high discard rates found in this fishery primarily resulted from mis-matches in regulations on minimum landing size and mesh sizes. The mechanisms determining the size selection of fish are well documented but due to the irregular morphology of *Nephrops* and their poor swimming capacity, the selection of this species has been regarded as being less predictable and therefore non-controllable. Paper II presents the results from an extensive study of *Nephrops* measuring the morphology that influence whether they will pass through a mesh or not. Subsequent simulations demonstrated that the selection process is predictable and that variation in mesh configuration to a high degree determine the effectiveness of size selectivity of a gear for this species. Another important result was a clear indication of *Nephrops* escaping through meshes along the entire length of the codend. This is in contrast to the escape of fish that primarily happen in the rearmost part of the codend. In the majority of trawl fisheries, the meshes in the codend are diamond shaped and as the catch accumulates, the increased drag will close the meshes. This will not happen in square meshes. Consequently, these meshes are often found to have better selective properties for a range of species including *Nephrops* and round fish (e.g. cod) whereas some species of flatfish escape more easily through diamond meshes. If the size selectivity of different species need to be considered in the same gear, a combination of different

mesh types could therefore be an option. How to distribute the different mesh types optimally in the codend will depend upon the preferred direction of escape of the different species. Paper III presents a study where fish and *Nephrops* escaping through meshes in the upper and the lower panel were collected in different collecting bags. Based on knowledge attained in this and the previous investigations, a codend was constructed with the lower panel made of square meshes and the other panels made of diamond mesh netting. For cod and *Nephrops*, the selective properties obtained for this combined codend were as good as those obtained for a plain square mesh codend whereas the size selection of plaice resembled that of a diamond mesh codend. The results from this experiment are presented in Paper IV.

The implementation of more selective fishing gears and management initiatives that focus on the catches instead of landings will contribute to the development of a more selective fishery. In the following review, a range of technological measures that can improve selectivity in the *Nephrops* directed fishery is presented.

1. Introduction

In the present thesis, discard is defined as the proportion of the catch hauled on deck that is returned to the sea, dead or alive. Discarding of target and non-target species is common practice in commercial sea fisheries across the world and it represents a considerable proportion of the global marine catches. It is estimated that 6.8 million ton are discarded annually while the total recorded landings amount to 78.4 million ton (Kelleher, 2005). The discard rate (discard / discard + landings) is fishery dependent and, globally, the highest rates (exceeding 60%) are found in some of the crustacean and demersal finfish trawl fisheries (Kelleher, 2005). Demersal trawling is one of the most important fishing techniques in use today. This fishery accounts for approximately 22% of the world's total landings but 50% of the total estimated discards (Kelleher, 2005). Consequently, the present thesis focuses on the discard of trawling.

Mortality of the discard varies but generally exceeds the survival (Broadhurst et al., 2006) and discard is therefore a waste of valuable resources, as well as a potential threat to the recovery of declining fish stocks (e.g. Harrington et al., 2005). The fate of the discards may also have profound effects on the ecology of the seabed as the fishery effectively transfers organic matter from the bottom to the surface. Here most of the organic matter in the form of fish and *Nephrops* (*Nephrops norvegicus*) is removed for human consumption or by seabirds. On the way back through the water column, some of the discard may be eaten by fish but finally, the remaining part of the organic matter that was removed by the trawl, is returned to the sea bed. A fraction of this will be capable of surviving while the remaining part will become eaten or decay (Evans et al., 1994).

High discard rates have been reported from most *Nephrops* fisheries (e.g. Bay of Biscay (Macher et al., 2008), Celtic sea (Rochet et al., 2002), Clyde Sea (Bergman et al., 2002), Kattegat and Skagerrak (Paper I; III; IV), Mediterranean (Sala and Lucchetti, 2010), North Sea (Catchpole et al., 2005b), South of Portugal (Campos et al., 2002),). In 2009, Danish landings of *Nephrops* from Skagerrak and Kattegat amounted to 2141 ton, and 1440 ton respectively and another 875 ton were taken in the North Sea. The *Nephrops* directed fisheries in Kattegat and Skagerrak are mixed species fisheries and besides *Nephrops*; plaice (*Pleuronectes platessa*), cod (*Gadus* *morhua*), saithe (*Pollachius virens*), witch flounder (*Glyptocephalus cynoglossus*), and haddock (*Melanogrammus aeglefinus*) constitute an economically important part of the catch. In value, *Nephrops* make up 11% of the total Danish fishery (excluding the industrial fisheries) and both in Kattegat and Skagerrak, *Nephrops* is in value the most important demersal species (Based on landings in 2009, Ministry of Food, Agriculture and Fisheries. The Danish Directorate of Fisheries). In these areas, the minimum mesh size (MMS) in the codend is 90 mm when targeting *Nephrops* (EC No. 40/2008)[1]. This codend has a high retention of undersized target and non-target species. Investigations have shown that about 50 % of the *Nephrops* caught with this gear are below MLS (40 mm carapace length) (Paper I; III; IV). Furthermore, based on on-board-sampling in the commercial fishery conducted in accordance with the EU data-collection framework (DCF, Council Regulation 199/2008), the total discard to landing ratio in the Skagerrak demersal fishery[2] in 2002 is estimated to be 0.86. This indicates that for one kilo landed fish and *Nephrops* 0.86 kg was discarded (Andersen et al., 2005). The highest discards were found for saithe, haddock, plaice, cod, and *Nephrops*. In Kattegat the discard ratio was estimated to be 1.2 in 2002 with plaice, dab (*Limanda limanda*), flounder (*Platichthys flesus*), whiting (*Merlangius merlangius*), and *Nephrops* dominating the discards (Andersen et al., 2005). In particular discard of cod is causing concern, as the International Council for the exploration of the Seas (ICES) states that the stock is at a historically low level in the Kattegat and overfished in the Skagerrak (ICES, 2010a; ICES, 2010b). The state of the *Nephrops* stock is unknown, but commercial landings per unit effort have been increasing in recent years suggesting that the stock is being exploited sustainable (ICES, 2010c).

Disregarding temporal and spatial closures, the most common way of addressing the issue of discard in trawls has been to modify the fishing gears and the way they are fished (Broadhurst et al., 2006). The objectives of the present Ph.D thesis have likewise been to investigate different ways to reduce discards of all commercial species in the Danish *Nephrops* directed fishery through gear improvements. An important element has been to obtain a better understanding of species selectivity in the fishery and of size selectivity of *Nephrops* in general. This was conducted in steps.

[1] If using a grid, a 70 mm square-mesh codend is allowed.

[2] Until 2004 it was allowed to use 70 mm ("*Nephrops* trawl") or 90 mm ("demersal trawl") codends for catching *Nephrops* and approximately 40 % of the *Nephrops* landed were taken in the "demersal trawl". Data from this fishery is used for comparison in this study as this is the mesh size used today.

First, gear trials were conducted to estimate the selectivity of the gears already implemented in legislation for the areas (Paper I). These findings on selectivity (Paper I; III) were combined with data on *Nephrops* morphology obtained in a detailed laboratory study in order to simulate the selection process of *Nephrops* (Paper II). Performance of different mesh configurations was investigated and to evaluate the possibilities of separating species vertically in the codend, behavioural preferences in direction of escapement of *Nephrops*, cod, haddock, whiting, and plaice were investigated by making use of a novel design of collection bag (cover) (Paper III). Finally, all the above findings on selectivity of different gears, on *Nephrops* morphology, and on behaviour in the codend were used to develop a more selective codend (Paper IV). All gears were tested on board commercial fishing vessels as recommended to approximate commercial praxis (Wileman et al., 1996).

In the present review, the mechanisms leading to discard are outlined and the *Nephrops* directed trawl fishery is described. Different methodologies are used to evaluate the selectivity of fishing gears and their strength and weaknesses are discussed. Finally, means to reduce discards by improving species - and size selectivity of the gears, and by management measures are presented and discussed.

2. Cause of discard

Discarding occurs when the catch composition hauled on deck is different from what the fisher will bring to the market. In short, what species and sizes are landed are determined by three factors; (i) catch composition, (ii) regulations, and (iii) market values. The relative importance of each factor is fishery specific and understanding these drivers will help identifying the optimal strategy for reducing unwanted catches in the fisheries in question.

2.1. Catch composition of a trawl

In simplistic terms, the trawl can be regarded as a filtering device where the species and size distribution in the path of the trawl represent the potential catch composition. This distribution is determined by the area and depth in which fishing is conducted, and within this zone, distribution also changes over the season according to growth patterns and migration. Other factors such as time of day and tide will also influence the distribution of sizes and species encountered by the trawl. Whether or not an organism in the path is actually retained by the trawl and in turn becomes a part of the catch, is determined by the efficiency and selectivity of the gear. This is dealt with in detail in later chapters.

2.2. Regulations

As for most other fisheries, the regulations laid down for the *Nephrops* directed fisheries intend to protect juveniles (e.g. Council Regulation (EC) No 850/98 for the conservation of fishery resources through technical measures for the protection of juveniles of marine organisms) and ensure a sustainable exploitation of the stocks (e.g. EC No. 219/2110, EC No. 23/2010, EC No. 43/2009). A range of regulations is in force in Kattegat and Skagerrak and the aim of this text is not to give a complete picture of the management in the area, but rather to illustrate that such regulations may directly lead to discarding.

Regulations on minimum landing size (MLS) and minimum mesh size in the codend (MMS) are often applied as they are easy to control. In a single species fishery, they can be matched to minimize catches of unwanted size groups. However, fisheries are very often targeting several species with differing morphology and sizes. This may result in a mismatch between MLS and MMS at least for some of the species (Paper I;

III; IV). This is the case in the Danish *Nephrops* directed fisheries in Kattegat and Skagerrak where demersal trawls are used on *Nephrops* grounds where cod, haddock, and plaice constitute an important part of the valuable catches. MMS is set at 90 mm to retain the relatively small *Nephrops* but this mesh size results in high discard rates of individuals below MLS for all species including *Nephrops*[3]. Besides MMS, regulations also limit twine thickness[4] and circumference of the codend as both parameters have a negative relation on size selection.

Total allowable catch (TAC) is a management measure that is used to control fishing mortality of a single population of fish. In mixed species fisheries the vessels normally have a set of quotas (fraction of the TAC), and in most cases the fishery will continue until all the quotas are exhausted[5]. For longer or shorter periods, the fisher is therefore obliged to discard species for which he has no quota, while using up the quotas on other species. In Kattegat and Skagerrak, quotas on cod are often used up first whereas the TAC on *Nephrops*[6] has not been fully exploited during the last 5 years (Ministry of Food, Agriculture and Fisheries. The Danish Directorate of Fisheries).

As illustrated above, management systems based on regulation on landings often, albeit unintended, can result in high levels of discards (Crean and Symes, 1994). Alternatively, the fishery may be regulated through limitations in the effort, i.e. number and size of vessels in the fishery and / or a limitation in the number of days at sea. This may reduce discards but also the revenue of the fishery because the amount of landings will be constrained. Unless the efficiency of the fleet is regulated, this may be increased to mitigate the economic loss and the reduction in discard will consequently fade away. Today, fishing effort in Kattegat / Skagerrak is limited and this may force some of the fishing activities to move to other areas.

Finally, some countries have banned discards (Kelleher, 2005) while others make it illegal to discard fish that may be landed legally (EC No. 43/2009). Both measures reduce discards, but they are difficult to control.

[3] MLS size for *Nephrops* caught by Danish vessels is 40 mm carapace length (EC No. 850/98)

[4] Maximum diameter of the codend twine is 8 mm if single twine and 6 mm if double (EC Re. No. 850/98)

[5] In Skagerrak, only gears that are documented to have a minimum by-catch of cod are allowed once 90 % of the cod quota is used (EC No. 23/2010)

[6] The total Danish *Nephrops* TAC was 6792 tonnes in 2009 of which 4456 was fished

2.3. Market value of the landings

At any given trip, the vessel owner will aim at optimizing the value of the landings. If either the quota, the holding capacity, or the capacity of the crew is limiting the quantity that can be landed, the most valuable species and sizes will be chosen (Rochet and Trenkel, 2005). This may result in "high-grading" where the small but legal sized are discarded in order to retain more of the bigger and more valuable ones. The market value is dynamic and will adjust when new markets appear or disappear. This has been the case for the English north-east coast *Nephrops* fishery where developments in processing technology have created a market for small sized *Nephrops* that are now 'tailed' before landing (Catchpole et al., 2002). Prior to this market development, the small sized *Nephrops* were discarded.

3. *Nephrops* – an introduction

Before we go into further details about the fishery, a brief introduction of the target species of this thesis is appropriate. *Nephrops* (Fig. 1) is an arthropod crustacean of the order Decapoda and is often referred to as Norway Lobster, Prawn, Langoustine, Dublin Bay prawn, or Scampi.

Fig. 1. *Nephrops norvegicus* sitting in a burrow entrance. Photo: Henrik Manley

They grow to a maximum total length of 25 cm (including the tail and clawed legs) and live on muddy substrates at depths ranging from 15 to 800 m. Geographically, they are widely distributed on the continental shelf of the North East Atlantic and in the Mediterranean Sea - off Iceland in the North and as far south as Morocco (Chapman, 1980). *Nephrops* construct 20-30 cm deep burrows which are used as refuges and they only leave them to forage or mate (Bell et al. 2006). They are consequently confined to areas where the sea bed consists of fine cohesive mud, stable enough to support the unlined burrows (Chapman and Rice, 1971; Rice and Chapman, 1971). The burrow systems can be complex and extensive with several entrances (Rice and Chapman, 1971).

The sexes can be distinguished by differences in the 1st pair of pleopods. On males, these are pointed and form a forward pointing tube while those of the female are smaller, flexible and non-tubular. Females mature when they are approximately 3 years old while males are not mature until 4 years old (Tuck et al., 2000; Ulmestrand and Eggert 2001). After spawning, the females carry the eggs on the abdomen until hatching and release of the larvae. After a short planktonic stage, the larvae moult and take on the form and habits of the adults, becoming bottom dwelling and constructing burrows (Bell et al. 2006).

Nephrops spend most of the time in their borrows where they are unlikely to get caught by trawl nets. Emergence therefore determines the size of the commercial catches which are known to vary depending on biological and environmental factors such as moult cycle, female reproductive condition, ambient light level, season, area, and tides (Chapman, 1980). They are scavengers and feed on a variety of organisms including polychaete worms, crustaceans, mollusks and echinoderms (sea urchins). In the Kattegat and Skagerrak area, mainly cod prey upon *Nephrops*.

Above the seabed, *Nephrops* react to disturbance by rapidly flipping the tail which propels them backwards. Average swimming speed is 1 – 1.5 knot and field observations have indicated that reaction distance is 0 – 55 cm (Newland and Chapman, 1985; Newland and Chapman, 1989). To be caught by the trawl, they must be induced to swim up and above the footrope. Although bigger animals are able to elevate themselves up to 85 cm from the substratum the mean height of the swimming path has been found to be 20 – 50 cm (Newland and Chapman, 1985).

4. *Nephrops* trawling

Nephrops are fished all the year round, and the trawls used in the Danish fleet range from small trawls with low headline designed exclusively for catching *Nephrops* to large whitefish trawls with high headline designed to catch haddock and saithe. The majority of the *Nephrops* are caught in a multispecies setting where gadoids, flatfish, and *Nephrops* are caught together due to their sympatric abundance on the fishing grounds (Ulrich and Andersen, 2004; Andersen et al., 2005).

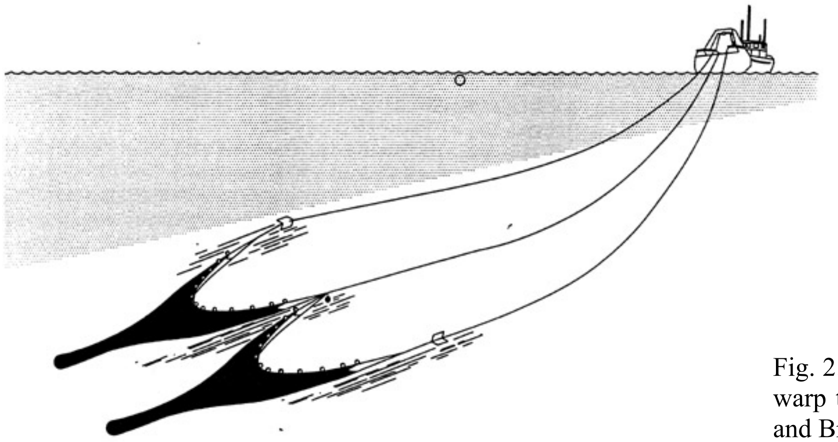

Fig. 2. Twin trawl with a three warp towing system (Sangster and Breen, 1998).

The trawl designs used in this fishery are combined *Nephrops* and fish trawls; so-called "combi-trawls", designed to catch and retain most of the species of commercial interest. They are mostly towed in twin-rig systems where two small trawls of the same design are rigged together and towed by the same boat (Fig. 2). Compared to single trawls, this system reduces the amount of netting per unit swept area which again reduces the drag of the gear (Fig. 3).With the same towing power, it is therefore possible to achieve a greater horizontal spread (20–30%) (ICES, 2004), which results in increased catches of ground species such as *Nephrops* and flatfish (Sangster and Breen, 1998). Fishing takes place on soft bottoms and the ground gear consists of rubber cookies where additional chains may be used to ensure bottom contact. Towing speed is usually 2-3 knots and with a

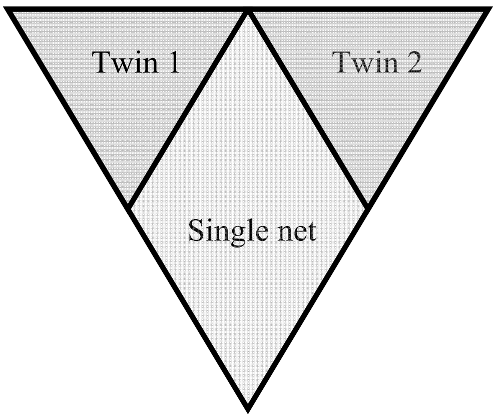

Fig. 3. Representation of single and twin trawls having the same width (ICES, 2004)

swimming speed of 0.5 to 1.5 knots, *Nephrops* in the path of the net will quickly be overtaken by the ground gear (Main and Sangster, 1985a; Newland and Chapman, 1989). About half of the fully emerged animals have been found not to react before they are touched by the gear (Newland and Chapman, 1989), making efficiency of the gear highly sensitive to good contact with the seabed.

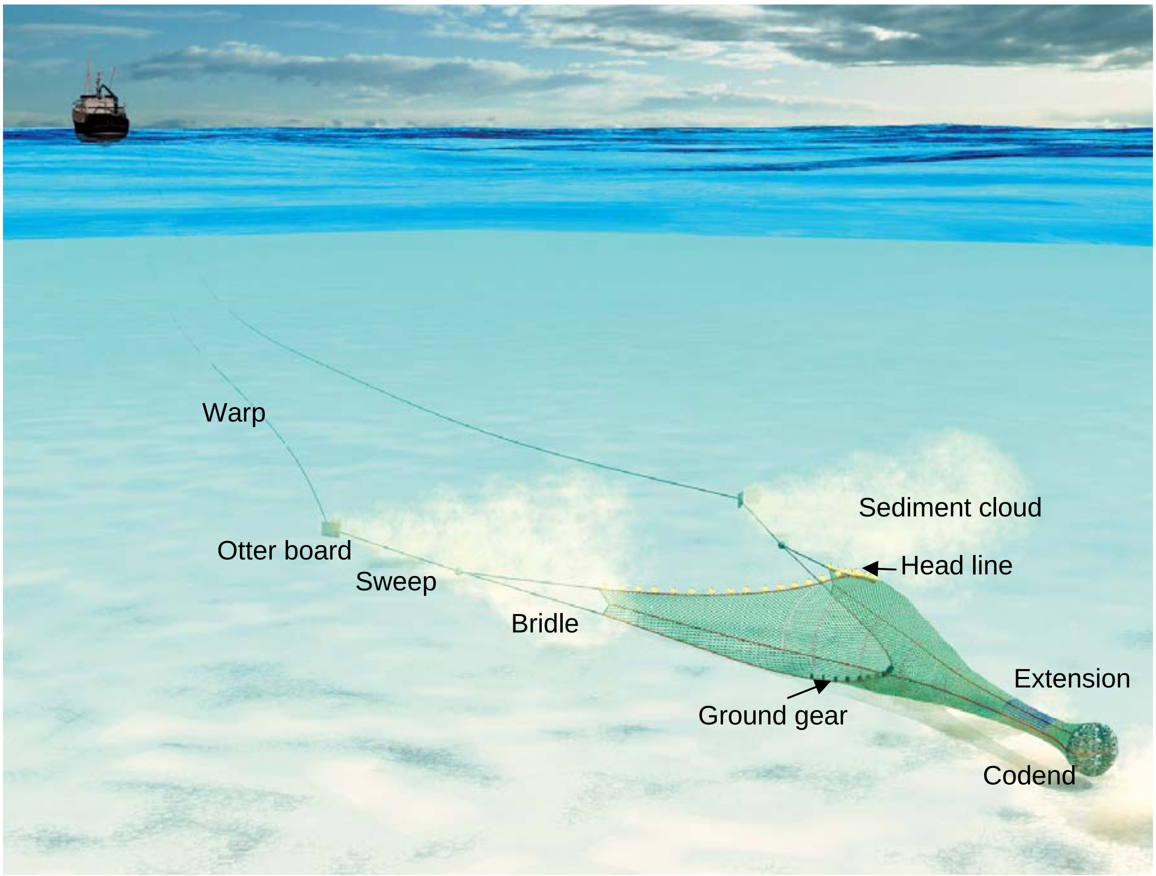

Fig 4. Drawing of an otter trawl. (Crown Copyright, reproduced with the permission from Marine Scotland – Science.)

Gadoids and several other fish species, are herded by the otter board, the sweeps, the bridles, and the wings and thereby guided into the area swept by the trawl netting (Fig. 4) (Wardle, 1989; Handegard and Tjøstheim, 2005). Once inside the trawl, the fish will try to avoid the netting until they reach the codend where most of the size selection occurs (Beverton, 1963; Wardle, 1993). *Nephrops*, on the other hand, are limited in their swimming ability and herding by the sweeps and bridles is therefore either insignificant (Main and Sangster, 1985a) or greatly limited by the angle of attack and the distance to the trawl netting (Newland and Chapman, 1989). If they are in the swept area, they will react to the ground gear either by (i) retrieving into their borrows and thereby escape the gear or (ii) flip their tail to raise about 50-60 cm from the sea bed (Main and Sangster, 1985a). As described in section 3, *Nephrops* register the approaching trawl less than 1 second (assuming a towing speed > 1 ms^{-1}) before it arrives and retrieving into the burrows is therefore only possible if they are already at the entrance. Visual observations have shown, that once inside the trawl, *Nephrops* roll along the lower sheet of netting all the way back to the codend (Main and Sangster, 1985a; Robertson and Ferro, 1991; Briggs and Robertson, 1993) where they primarily escape through the meshes of the lower netting (Paper III). As they are in contact with the netting, escape through meshes is possible in the entire length of the gear. Escape from sections forward of the codend have been observed by Main and Sangster (1985a) and Hillis and Earley (1982) whereas Robertson and Ferro (1991) anticipated escapement in this part of the trawl but did not observe it. The whole capture process of each individual *Nephrops* takes no longer than a few minutes (Robertson and Ferro, 1991).

5. Selectivity of trawls

5.1. Species selectivity

In most demersal fisheries there is a by-catch of unwanted species that will subsequently be discarded. By changing the design of the gear it may be possible to reduce catches of these species and thereby increase the species selectivity of the gear. Behavioural differences between species are often exploited to separate them somewhere in the catching process. Direct observation of fish reaction to fishing gear was initiated with underwater television vehicles in the 1970s and advances made in optical, acoustic and data-processing technologies have continuously been applied to the field (Graham et al., 2004). Despite these technological advances, the environment in and around a trawl gear still challenges the equipment. In particular the lack of visibility due to re-suspension of sediment and the rapid reduction of natural light at depth may cause divergence between visual observations and actual catch (Krag et al., 2009b). The methods for direct observation of behaviour is therefore suited for qualitative investigations but alternative methods for quantifying the reaction of fish to different netting panels are needed (Krag et al., 2009b). Such a quantitative assessment of how a new gear performs with regard to reduction or increase in catches of different species is demanded both by fishery managers and fishers. For this purpose, specialized collecting bags are used to collect escapees (Paper III; Engås and Godø, 1989a; Krag et al., 2009a; Krag et al., 2010) or where a unmodified "standard" trawl is fished parallel to the "selective" trawl in a catch comparison setup (e.g. Holst and Revill, 2009). In the former case, it is assumed that the collecting bags do not themselves affect fish behaviour or the catchability of the gear whereas the latter rely on the assumption that the catch in the "standard" trawl reflect the populations of fish and *Nephrops* that were encountered by the "selective" trawl.

5.2. Size selectivity

The size selection of fish and *Nephrops* in a fishing gear can be defined as the process which causes the size distribution of the catch to be different from that of the fished population (Wileman et al., 1996). The size selectivity of a gear can either be assessed <u>relatively</u> by comparing catches in the "selective" trawl with catches in a "standard" trawl or <u>absolutely</u> by estimating the size distribution of fish that entered the trawl codend and relating this to what was retained (Table 1).

Table 1. Overview of the advantages and drawbacks of the different methods for estimating size selectivity of trawls

	Experimental setup	**Strength**	**Weakness**
Relative selectivity	Catch comparison	– Test under commercial practice – Whole gear selectivity	– Many fish needed – Estimates can only be used for comparison of gears included in the test
Absolute selectivity	Covered codend	– Exact estimate of the total number of fish entering the codend – Possible to estimate selection of different components by splitting the cover	– Risk of cover effect – Difficult to handle on board small vessels
	Paired gear	– Easy to handle on board small vessels – No risk of interfering with the gear under test	– Reliable estimation of relative fishing power (*p*) is essential and a sufficient number of large individuals are needed to do this – Indirect assessment of the total number of fish entering the gear under test making it sensitive to proper choice of type of selection curve – Risk of bias/increased statistical error in estimates particularly in case of few fish

The former estimate allows testing the gear in accordance with commercial practice and the estimates are useful for evaluating gain or loss attained if a new gear is implemented (Holst and Revill, 2009). The relative estimate can, however, only be used for comparing the gears that were included in the test. In contrast to the absolute method, which often focuses exclusively on the codend, the relative estimate takes the selectivity of the whole gear into account.

Functions on the form $r(l) = \frac{\exp(f(l))}{1+\exp(f(l))}$, with f being modeled as a polynomium of some order, are fitted to describe the relative catch efficiency for each length group and in most cases, there is no a priori knowledge on the course of the retention curve, i.e. no structural limitations except that the value should be confined to a value between 0.0 and 1.0. This lack of fixation renders the method highly volatile and increases its sensitivity with regard to the number of fish in each haul. Therefore, a large number of fish in each length group is needed to establish a reliable estimate. On the other hand, the absolute estimation, provides gear specific parameter estimates and allow subsequent comparison with other gears. In the following, attention is given to the assessment of absolute selectivity of the codend.

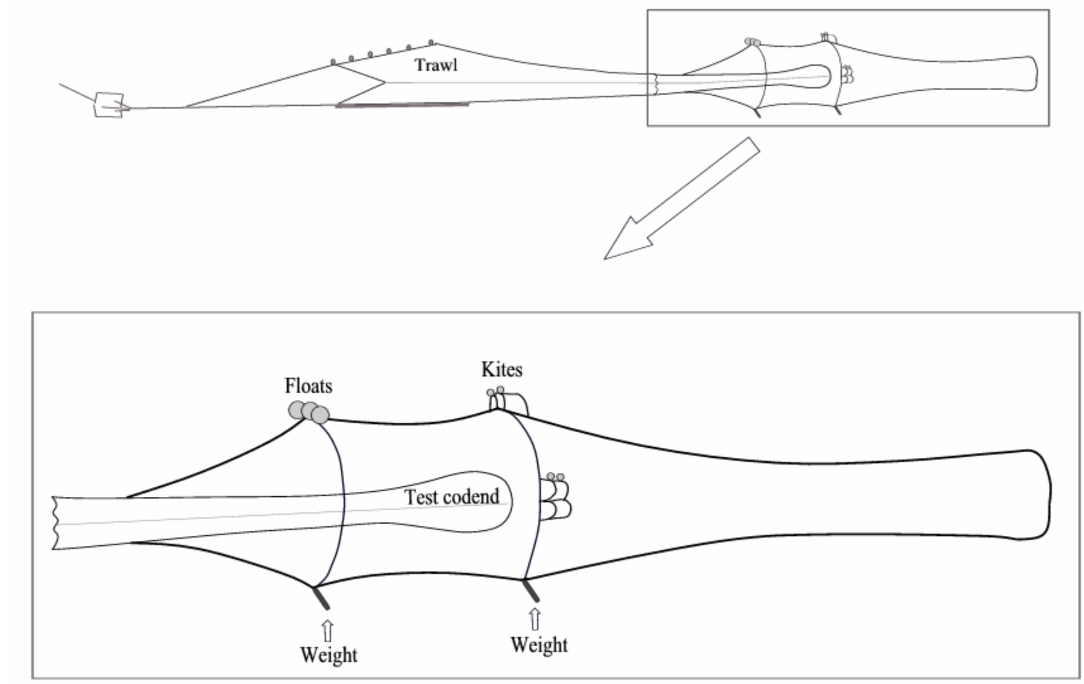

Fig. 5. Codend cover with kites for opening the cover to keep it clear of the codend. Drawing: Niels Madsen, DTU Aqua

The absolute parameter estimates describe the retention rate for each length group, i.e. the chance that a fish of a given size will be retained by the codend. The estimate is based on knowledge of the total number of individuals of each length group that entered the codend and the number that was retained. The total number can be measured directly by use of the "covered codend" methodology where all escapees are collected in a small meshed "non-selective" cover (Fig. 5) (This methodology was used in Paper III and Paper IV). Alternatively, the total numbers that enter the codend can be estimated by the "paired gear" methodology where a small meshed "non-selective" codend is fished parallel to the test codend. The codends are fitted to identical trawls e.g. in a twin trawl setup (Fig. 2) (this methodology was used in Paper I).

Which method to choose depends on the gear under test and on the conditions under which it is fished (summarized in table 1). If a long cover is needed and the experiment is conducted on board smaller vessels it may be difficult to handle. However, in cases where separate selection estimates of additional selective devices (e.g. grids or escape windows) are needed, the covers can be designed to meet this. The paired gear method, on the other hand, is well suited for use on small vessels especially if they are rigged for twin-trawling as this will ensure that the two trawls are fished under similar conditions. Alternatively the two trawls of the paired gear setup can be towed parallel by different vessels but this will increase variation and increase the number of hauls needed to evaluate the gear.

The retained proportion of fish of any given size group is estimated by relating the number of fish retained in the codend under test to the total number of fish that entered (or is estimated to have entered). In a simple codend, the proportion of fish and *Nephrops* retained by the gear increases with size. To be able to compare selectivity between gears and trials, a parametric curve is preferred. Several different curves can be applied e.g. the probit curve (normal probability), the Gompertz (log-log), the Richards curve, or the logistic curve and the one with the better fit statistic is chosen (i.e. a combination of high R^2 and high p-value as well as a low AIC). The logistic curve (formula (1)) is often applied as a starting point and used if there is no indication of it not being able to explain data well. The reason for this is that it is simple to model and its shape can be described by just two parameters; the length at which 50 % of the fish is estimated to be retained (L_{50}) and the selection range which is the difference between the length for 75 % retention and 25 % retention ($SR = L_{75}-L_{25}$) (Fig. 6).

(1) $$r(l)=\frac{\exp\left((l-L_{50})\times\frac{\ln(9)}{SR}\right)}{1+\exp\left((l-L_{50})\times\frac{\ln(9)}{SR}\right)}$$

Where $r(l)$ is the estimated retention rate at length l. A maximum likelihood function is used to estimate the values of L_{50} and SR that makes the observed retention rates (= the experimental data) are most likely. The method is described by Wileman et al. (1996).

For the covered codend methodology, the approach is straight forward as the retention rates are estimated as the fraction of the total catch retained in the test codend as given in formula (2).

(2) $$R(l)=\frac{n_{lTest}}{n_{lTest}+n_{lCover}}$$

Where R is the experimentally obtained retention rate at length l, n is the number of individuals, *Test* and *Cover* refers to the test codend and cover respectively (see Fig. 5). R will approximate 0 for smaller length groups and 1 for the length groups that cannot physically escape through the meshes. Likewise, retention rates from a paired gear trial can be obtained as shown in formula (3) where the "total" catch is estimated as the sum of the catch in the test codend and the "non-selective" control codend (*Control*).

(3) $$R(l) = \frac{n_{lTest}}{n_{lTest} + n_{lControl}}$$

This approach is commonly known as SELECT (Share Each Lengths Catch Total) and it is the most widely used methodology for analyzing paired gear data (Millar, 1992). Due to the nature of the paired gear setup, R for larger length classes will approximate the relative fishing power p which is < 1. If the two codends fished with exactly the same power, p would be 0.5 but despite the best efforts while conducting the selectivity experiment this is often not the case. The extra parameter p, which is also denoted as the split factor, is estimated together with SR and L_{50} when fitting the experimentally obtained retention rates to a logistic selection curve (formula (4)) by use of a maximum likelihood function. The estimated retention rate (ϕ) thus ranges from 0 to p.

(4) $$\phi(l) = \frac{p \times \exp\left((l - L_{50}) \times \frac{\ln(9)}{SR} \right)}{(1-p) + \exp\left((l - L_{50}) \times \frac{\ln(9)}{SR} \right)}$$

The estimation of an additional parameter adds to the uncertainty of the estimate and, depending on the parametric curve used as well as the method for analysis, this can result in bias (Herrmann et al., 2007a) or increased statistical error (Millar, 2010) of SR and L_{50}. This is in particular the case when the number of individuals is low.

Generally, the selectivity of a gear is regarded to be improved if L_{50} is increased and SR is reduced. The extreme situation is a knife-edge selection where SR is close to zero and L_{50} can be adjusted to fit the MLS. In a single species fishery this would eliminate loss of marketable catch as well as discard of undersized catch (Fig. 6). Due to variation in the selection process, the result is never "knife edge". This variation can result from morphological differences, variation in mesh openings, and variation in the contact between the specimen and the netting. Assuming that the appropriate stimulus is present to encourage the fish to attempt to escape, the outcome (success or failure) of the attempt is determined by the morphology of the fish and the actual shape of the mesh.

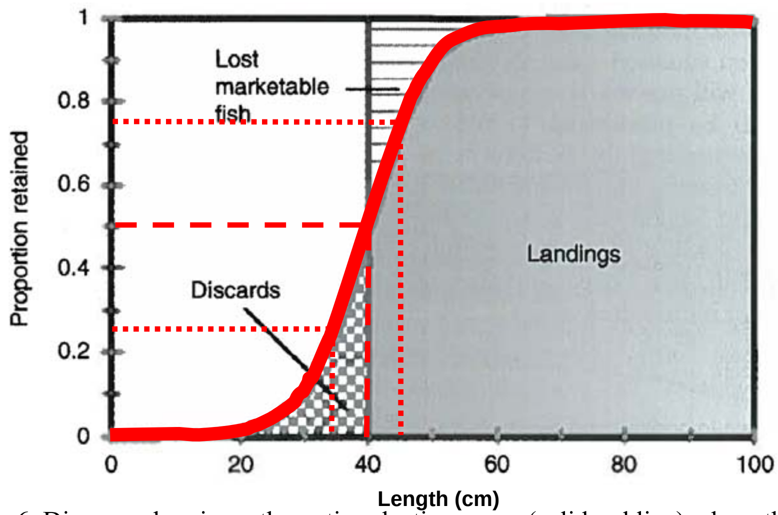

Fig. 6. Diagram showing a theoretic selection curve (solid red line) where the MLS is assumed to be 40 cm. In this case, L_{50} (broken red line) equals 40 cm as well and *SR* equals 10 cm (dotted red lines indicate L_{25} and L_{75}) (Cook, 2003).

Simulation of the catch process (Herrmann et al., 2009) indicate that the majority of variation in selectivity within and between hauls may be explained by the variation in mesh shape. The meshes in different sections of a diamond-mesh codend open and close as the catch builds up (See section 6.2.3). A fish caught in the beginning of a haul is therefore not met with the same scenario of meshes as a fish caught towards the end. Square-mesh codends, on the other hand, are more stable in their mesh configuration resulting in less variation in the selection process and these codends can therefore theoretically obtain a sharper selection curve (i.e. smaller *SR*).

5.2.1. Size selection of *Nephrops*

Compared to the selection curve of many fish species for the widely used diamond-mesh codends, that of *Nephrops* is shallow i.e. has a relatively high *SR* (Briggs, 1986). One reason for this problem is assumed to be the irregular shape of *Nephrops* (e.g. Briggs, 1986). Furthermore, the towing speed of the trawl largely exceeds the swimming speed of *Nephrops,* and their orientation when encountering the netting is therefore assumed to be random. Observations of *Nephrops* behaviour in the gear confirm this, as they have been seen to roll along the lower sheet of netting (Main and Sangster, 1985a; Robertson and Ferro, 1991; Briggs, 1992; Briggs and Robertson, 1993). To some extent, this has characterized the problem as insoluble. However, as proven in paper II, the selection process in the codend can be simulated by simply regarding the morphology of *Nephrops* and combining this with the assumption that *Nephrops* uses the entire length of the codend for escape. The study used the FISHSELECT methodology (Herrmann et al., 2009) and it was found that “randomness” in the orientation of *Nephrops* could be explained by taking three different modes of orientation into account (Fig. 7).

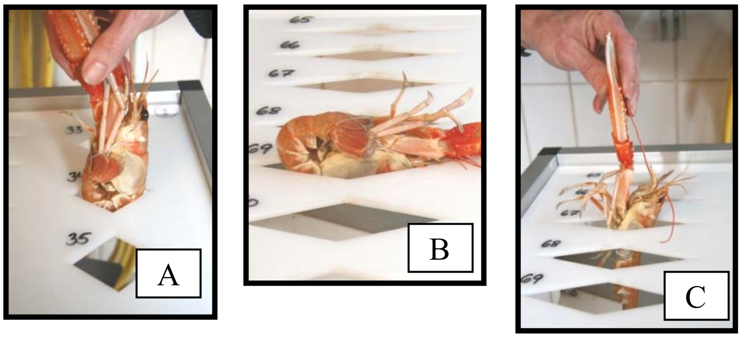

Fig. 7. Modes of orientation of *Nephrops*. Mode A is expected to occur in 5.8% of all escapes through codend meshes while mode B and C are expected in 6.7% and 87.5% of all escapes.

The selective properties for each mode can be described by a design guide where the simulated L_{50} is plotted against mesh size and opening angle of the mesh (For details see: Herrmann et al., 2009). Each of the three modes has a unique design guide for any given mesh shape, and those for diamond, rectangular, and hexagonal meshes are shown for mode B and mode C (Fig. 8). Modes B and C represent the largest and the smallest cross section respectively. When held together, they can be used to estimate the carapax length of the smallest individual that may be retained and the largest individual that may escape if they meet a given mesh. The findings presented in Paper II enabled a scrutiny of the selection process of *Nephrops*. This revealed that escape take place in the entire length of the codend and that in a 6 meter codend, 87.5 % of the *Nephrops* were oriented optimally i.e. in mode C when they escaped through the meshes. Furthermore, it was found that the variation in opening angles in diamond-mesh netting, depending on distance from the catch build-up, contributed considerably to the variation in the chance of escape (Fig. 10D in Paper II). A high variation in the chance of escape automatically results in a high *SR*. Reducing the variation in mesh configuration in the selective part of the codend can thus be used to reduce *SR* of *Nephrops*.

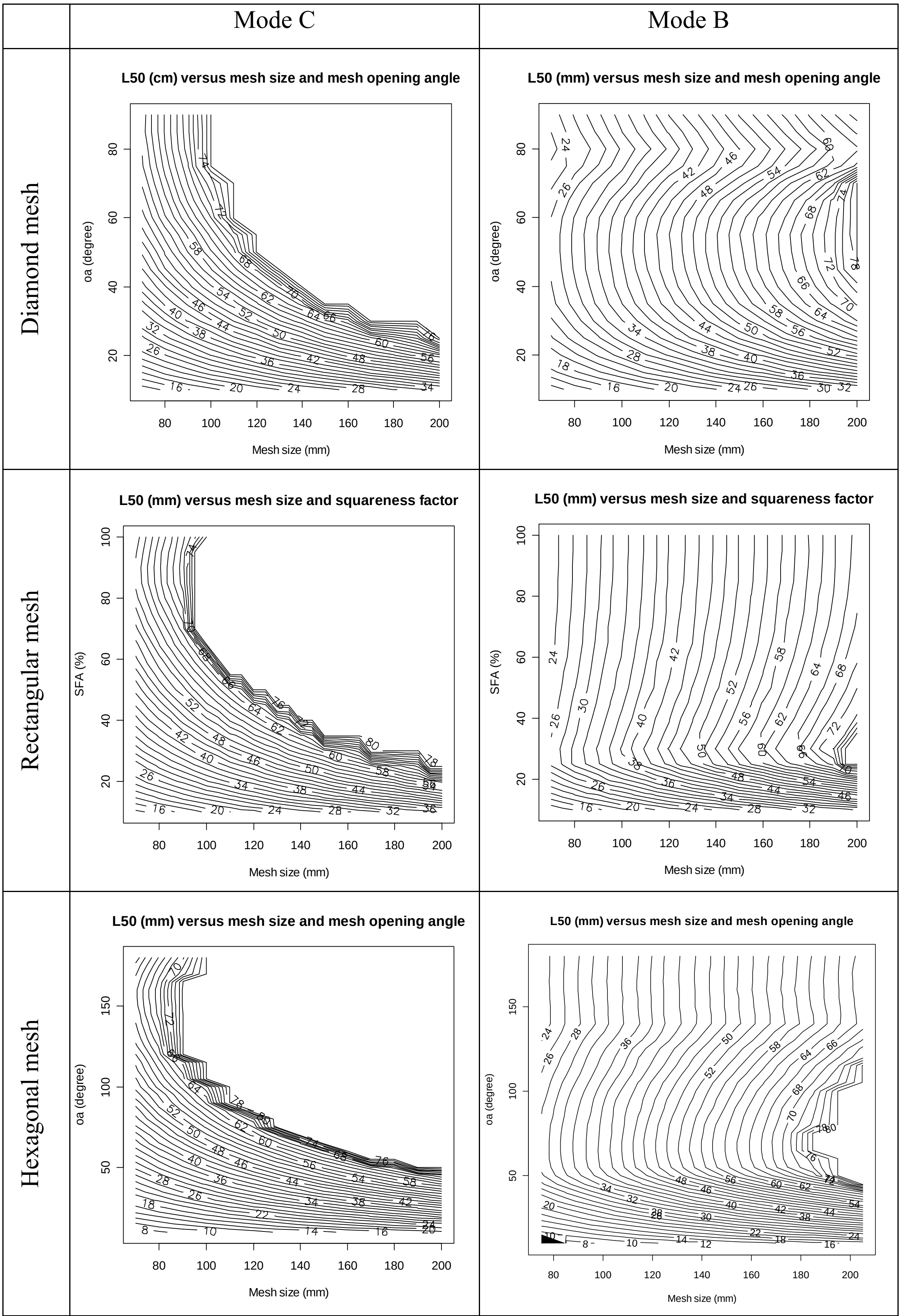

Fig. 8. Design guides for *Nephrops* in Mode C and Mode B in diamonds, rectangels and hexagonals. Isolines show combinations of mesh size and opening angle with equal L_{50}. The SFA value for rectangles, indicate the ratio between the short and the long bar. For further description of mesh configuration see Herrmann *et al.* (2009).

Using structural models such as FISHSELECT also allows prediction of selectivity of codends that have not yet been tested experimentally. The predictions can not replace the sea trials but they will provide better starting points and thus potentially reducing the number of sea trials needed. Sea trials are both expensive and time consuming and time and money spend in the process of gear development may therefore be reduced.

6. Mortality of escapees vs. mortality of discards

The consequences of introducing gears with increased selective properties to commercial fleets clearly depend of the fate of the fish that escape through meshes compared to the fate of the fish being discarded.

A series of studies with focus on the survival of both escapees and those discarded have been conducted and in a review, Broadhurst et al. (2006) conclude that the escapees have a better chances of survival. It is stated that escape mortalities range between 0 and 100 % but more commonly are less than approximately 20 %, whereas the estimated proportions of discarded individuals dying often greatly exceeds the proportion surviving. The impairments are, however, species specific and they depend both on physical factors such as place and time of escape and for discards; technical factors, catch size, handling- and fishing practice, as well as environmental factors (e.g. Symonds and Simpson, 1971; Davis, 2002; Castro et al., 2003; Gamito and Cabral, 2003; Suuronen et al., 2005; Suuronen and Erickson, 2010). Survival of fish that escape through the meshes of the codend, through a grid, or through the escape hole in front of a grid has been investigated by collecting them and subsequently monitoring their survival in underwater cages. Cod, *Nephrops* and flatfish in general have high survival upon escape (van Beek et al., 1989; Sangster et al., 1996; Soldal and Engås, 1997; Wileman et al., 1999; Suuronen et al., 2005; Ingólfsson et al., 2007) while mortality of whiting and haddock is more variable (Sangster et al., 1996; Soldal and Engås, 1997; Wileman et al., 1999; Ingólfsson et al., 2007). Several of these studies have found that the smaller individuals experience higher mortalities than their larger conspecifics (e.g. Sangster et al., 1996). Most mortality has been found to occur within the first day (Main and Sangster, 1990) but stress that might result in delayed mortality e.g. due to weakened response towards predators may last up to 20 days (Ryer, 2004; Ryer et al., 2004; Davis, 2007). These mortality rates have been estimated for fish and *Nephrops* that escape the gear during towing but escapement is a process that does not end when the gear lifts off the bottom. Madsen et al. (2008) and Grimaldo et al. (2009) demonstrated that more than 20 - 66 % of all escapement happened during haul-back and while the codend is at the surface. The individuals escaping during theses stages of the fishing process are likely to suffer higher mortalities due to increased stress, in particular for those species with closed swim bladder, but also due to additional predation at the surface from seabirds that are very active around the vessel during hauling (Catchpole et al., 2006a). Consequently, gear modifications that induce escapement early in the fishing process should be preferred to increase the survival of the escapees and, when possible, one should avoid initial capture of unwanted fish rather than improve their chances of escape from the trawl.

Most of the biological, environmental and technical factors affecting escape mortality likewise affect discard mortality. Furthermore, the discarded organisms are also subjected to considerable additional stress associated with being brought to the surface, exposed to air, thrown from the vessel and then sinking or swimming back to their habitats (Symonds and Simpson, 1971; Davis, 2002; Harris and Ulmestrand, 2004). Mortality of discard varies depending on the overall fragility of the organisms and presumably also on their dependency of ending up on a specific type of substratum. If not taken by seabirds before they sink, and if discarded on *Nephrops* grounds, survival of *Nephrops* have been estimated to range from 0 - 48 % (Symonds and Simpson, 1971; Evans et al., 1994; Redant and Polet, 1994; Castro et al., 2003) with an additional mortality of > 30 % if discarded through low salinity layer (Harris and Ulmestrand, 2004).

7. Reducing discards – what can be done

Management strategies can either; encourage fishers to retain previously discarded organisms, restrict fishing to areas and times where discarding is known to be low, or prohibit fishing in some areas. These measures can be effective in some fisheries but they are often associated with either high ecologic or high economic costs. Modifying the gears used and their methods of operation is a more pragmatic approach that is less likely to economically impact the fishing operation. It is consequently one of the most common ways of addressing the issue of discard in trawls (Broadhurst et al., 2006).

7.1. Technological modifications of the trawl

The study presented in Paper I provided absolute estimates (see section 5.2.) of the size selection for nine species in a 90 mm diamond-mesh codend commonly used in the Danish *Nephrops* directed fishery. The results clearly demonstrate that the size selectivity is inadequate and results in large amounts of unwanted catch which is subsequently discarded. Though this is the first study providing selection estimates for several species in this type of codend, its shortcomings with regard to size selectivity has long been recognized. Several experiments have been conducted to change this and the achievements have been reviewed regularly, first by Briggs (1986), following in an ICES report (2004) and latest by Catchpole and Revill (2008). The selectivity can be modified by alterations either in the design of the trawl, in the rigging of the trawl, or in the way it is fished (Graham, 2010). The ultimate choice of modification is determined by the desired catch composition.

Whether or not an organism in the path of the trawl is retained depend on its behaviour, its size and morphology and finally on the chances for escape that it experiences on its way through the gear. Gear modifications aiming at reducing discards by targeting specific species and sizes often make use of both the behaviour (Paper I; III; IV) and the morphology (Paper I; II; III; IV). In the following, the modifications that are applicable for *Nephrops* trawls are divided into three major groups based on their position in the gear; (i) changes in rigging, (ii) changes in the front part of the trawl, (iii) changes in the extension and codend.

7.1.1. Changes in the rigging

Species specific differences in the response towards the approaching gear is the earliest stage at which the selectivity of the trawl can be modified. Several species of flatfish and roundfish have been shown to be herded by the cloud of sediment raised by the otter boards and by the approaching sweeps and bridles (Fig. 4) (Engås and Godø, 1989b; Wardle, 1993; Ryer, 2008; Winger et al., 2010). This behaviour funnels them into the path of the net itself where they become available for capture (Winger et al., 2010). In contrast, slow moving benthic species like *Nephrops* and shrimps are not herded (ICES, 2004) and fish by-catch in dedicated shrimp and *Nephrops* trawls can therefore be reduced by minimizing the length of the sweeps.

7.1.2. Changes at the mouth and in the body of the trawl

At the mouth of the bottom trawl, species specific behaviour determines the height at which the fish and *Nephrops* enter the trawl. Investigations from the forward part of the trawl have thus shown that haddock, whiting and saithe tend to raise by swimming upwards in the catching process (Main and Sangster, 1985b; Engås et al., 1998; Ferro et al., 2007; Krag et al., 2010), whereas *Nephrops*, cod, lemon sole, plaice, and monkfish stay close to the bottom (Main and Sangster, 1985b; Engås et al., 1998; Ferro et al., 2007; Krag et al., 2010). At this point, it is therefore possible to separate species by adjusting the position of the headline (Madsen et al., 2006; Revill et al., 2006; e.g. Chosid et al., 2008) and the proximity of the ground-gear to the bottom (Brewer et al., 1996; Sheppard et al., 2004; e.g. Krag et al., 2010).

<u>Separator panels</u>

Once the fish have entered the trawl, they usually stay clear of the netting panels unless the straight path is blocked (Glass et al., 1993; Glass and Wardle, 1995) but the above mentioned differences in behaviour can still be exploited for species separation. In the 1970s, underwater television vehicles provided means to observe fish reaction to fishing gear. Based on these information, the first separator trawls were developed and studied in Scotland in the 1970s and 1980s (Ferro et al., 2007). Main and Sangster (1985b) described the performance of such a trawl where a horizontal panel guided the catch into separate codends. When placing the separator panel 75 cm above the bottom, around 95 % of both haddock and whiting ended up in the upper compartment while 100 % of cod (few individuals), 99.2 % of the flatfish, and 99.3 % of the

Nephrops ended up in the lower codend. The result was promising and offered the possibility of adjusting size selectivity of specific species in one codend without considering the catch in the other codend. Separating species into two codends has since been tested in several other fisheries and an increase in the acuity of the separation has been investigated (e.g. Engås et al., 1998; Ferro et al., 2007; Krag et al., 2009a). However, as mentioned previously, plaice and cod constitute an important part of the discard in *Nephrops* directed fisheries and since they both end up in the lower codend together with *Nephrops*, these solutions are not suitable for reducing the discards in this fishery.

<u>Large mesh panels</u>

Panels of larger meshes or square meshes can also aid the escape of some species of juvenile fish. When inserting a 120 mm square-mesh panel in the upper panel of the trawl, 8.85 m from the extension, Briggs (2010) found that 54 % of the juvenile haddock and 65 % of the juvenile whiting escaped while there was no loss of *Nephrops*. Alternative positions of such panels have been investigated and it is concluded that the optimum position depend both on the trawl design and hauling practices (Armstrong et al., 1998; Revill et al., 2007).

7.1.3. Changes in the extension and codend

Fish will avoid the netting unless they are encouraged to do otherwise (Glass et al., 1995). As they move backwards in the gear the large cavity of the trawl narrows in and becomes a tapered or non-tapered funnel of netting called the extension which connects the trawl and the codend (see fig. 4). Some species, including haddock and cod, will try to swim against the flow towards the mouth of the trawl. But as exhaustion sets in, they will slow down and eventually enter this relatively confined section of netting. Here, crowding may disrupt their orderly behaviour and elicit randomly oriented burst-swimming behaviour which may cause collision with netting (Winger et al., 2010). This behaviour is likely to result in the requested escapement of small individuals and devices that can aid escape are often positioned here.

Furthermore, investigations of species specific behaviour in the aft end of the trawl, in the extension, and in the codend, have shown that *Nephrops* and plaice tend to remain low in the net (Briggs, 1992; Briggs and Robertson, 1993; Krag et al., 2009a), while cod have a more uniform vertical distribution (Krag et al., 2009a), and haddock and whiting stay high (Krag et al., 2009a). To investigate if these behavioural differences also determine the preferred direction of escape, a novel cover that separated the escapees based on which panel they had escaped through, was developed (Fig. 2 in Paper III). This cover provided additional quantitative information on the selection process in the *Nephrops* fishery which is often characterized by poor visibility in and around the trawl due to re-suspended sediment. In line with their vertical distribution in the codend, this study demonstrated that *Nephrops* escaped almost exclusively (85-93.7 %) through the lower panel, whiting escaped primarily upwards (66.8-90.9 %), and cod escaped both upwards and downwards. Haddock and plaice showed no preference in their direction of escape in contrast to their vertical distribution in the codend (Krag et al., 2009a). Results presented in Paper III further illustrate that the preferred direction of escape for some species (in particular cod) was size related whereas type of codend significantly affected direction of escape for others (haddock and whiting). It was suggested that the latter could be linked to the netting material.

<u>Codend modifications</u>

The most obvious technique to reduce the retention efficiency of a codend is to increase the mesh size. In general, larger meshes allow larger fish and *Nephrops* to escape (Glass, 2000; ICES, 2007; Krag et al., 2008) but often, such changes also lead to a reduction in the catch of marketable sized fish. Alternatively, the mesh shape of the codend netting can be changed.

Upon reaching the codend, the catch accumulates and this forces a codend made of the commonly used **diamond-mesh** netting, to take on a bulbous shape. At this stage, tension in the netting causes the meshes in the forward part of the codend to become almost entirely closed while a few rows of meshes just in front of the catch build-up will become more open. Turbulence, together with vessel-induced pulsing movements may provide an additional opportunity to escape just in front of the catch build-up by reducing the speed required to maintain station within the codend (Rose, 1995; Broadhurst et al., 1999). Most escape attempts of fish are seen through these few rows of open meshes (O'Neill et al., 2003; Jones et al., 2008) and the ease and speed with which the codend take on this bulbous shape is therefore affecting selectivity: Consequently, an increase in codend circumference often has a negative impact on selectivity (Reeves et al., 1992; Herrmann et al., 2007b; Sala and Lucchetti, 2010) as does an increase in twine thickness of the netting (Lowry, 1995; Briggs et al., 1999;

Herrmann and O'Neill, 2006; Sala et al., 2007). Likewise, catch weight has been found theoretically to affect selectivity in some codends (O'Neill and Kynoch, 1996; Herrmann, 2005). As mentioned in section 5.2.1, the variation in mesh configuration induce a temporal variation in the chances for escape but also a spatial variation determined by distance from the catch build-up.

Unlike diamond-mesh codends, a codend made of **square-mesh** netting retains its cylindrical shape regardless of catch volume. And since the tension in the netting does not force the meshes to close under load, the chances for escape are more constant along the entire length of the codend and throughout the haul (Paper II; Glass, 2000).

The optimal mesh configuration for selection of a specific species is determined by its cross section shape (Herrmann et al., 2009). For *Nephrops*, a square-mesh codend with the same nominal mesh size as a diamond-mesh codend will be more size-selective, i.e. have a higher L_{50} and a lower SR/L_{50} (Paper II; Paper III). Square-meshes also have good selective properties for roundfish such as cod (Paper III; Halliday et al., 1999), haddock (Paper III; Robertson and Stewart, 1988; Halliday et al., 1999), and whiting (Paper III; Robertson and Stewart, 1988).In Paper III, a 70 mm square-mesh codend was tested against a 90 mm diamond-mesh codend. The square-mesh codend was found to have significantly higher L_{50} for *Nephrops*, cod, haddock, and whiting while SR for these species was either reduced or slightly increased. In all cases the relative steepness of the selection curve expressed as L_{50}/SR was increased. This is in accordance with previous findings (Robertson and Stewart, 1988; Halliday et al., 1999). In Paper III, difference in size selection of plaice between the two codends could be explained by the difference in mesh size (70 mm vs. 90 mm). For some species of flatfish, previous studies have, however, reported lower values of L_{50} in square-mesh codends than in the equivalent diamond-mesh codends (Walsh et al., 1992; He, 2007). The results of the study presented in Paper III suggest the potential benefits of combining different nettings in the codend to improve the selectivity of a wider range of species in mixed species fisheries.

<u>Grids</u>

In a *Nephrops* trawl, the diameter in the extension is around 1 meter and it is therefore possible to block the entrance to the codend by a tilted grid with parallel bars (Fig. 7). Distance between the bars determine what can pass through the grid and everything larger than that, will be guided out of the gear through an escape hole. Survival of cod, whiting, and haddock that escape in such a setup has been found to be close to 100% (Soldal and Engås, 1997).

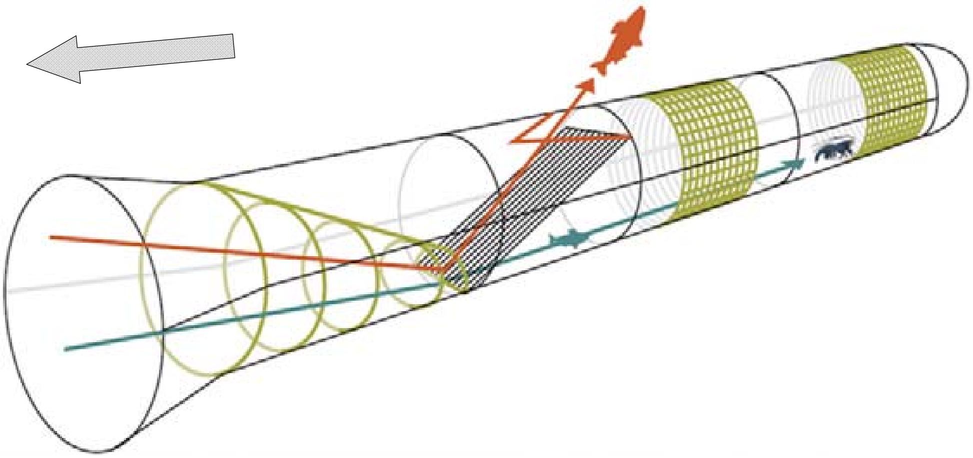

Fig. 7. Extension with a grid blocking the entrance to the codend. Arrow indicates towing direction. (Reproduced with the permission from Fiskeriverket / Swedish Board of Fisheries, Sweden)

The resulting catch is a clean catch of small individuals, which is desirable when shrimp or *Nephrops* are the only target species (Isaksen et al., 1992). In *Nephrops* directed fisheries, the "Swedish grid" is the most common design (Fig. 7). In combination with a 70mm square-mesh codend, it has been mandatory in Swedish national inshore waters since 2004 (Valentinsson and Ulmestrand, 2008), and in Kattegat/Skagerrak it was introduced in EU legislation as mandatory for 70-89 mm trawls in 2005 (EU regulation 27/2005). In 2009, areas in Kattegat that are otherwise closed to trawling to protect spawning cod, were opened to gear types with very low catches of cod. Among these are the "Swedish grid", again in combination with a 70 mm square-mesh codend (BEK. No. 391, April 16th, 2010). Bar distance in this grid is 35 mm and it is assisted by a panel that guides all catch to the bottom of the netting just in front of the grid (Fig. 7). The panel ensures optimal contact with the grid which is important to avoid loss through the escape hole. In catch comparison experiments (see section 5), the grid has been found to reduce catches of cod above MLS (MLS = 40

cm) by more than 99% while reduction of undersized cod was 71 % (Valentinsson and Ulmestrand, 2008). When testing the grid in the English *Nephrops* fishery, Catchpole et al. (2006c) similarly found a reduction of round fish but in contrast to Valentinsson and Ulmestrand, they experienced a loss of legal sized *Nephrops* of 40-

53%. The difference between the two experiments may by explained by a difference in MLS which is 40 mm carapace length (CL), in Kattegat and Skagerrak, where Valentinsson and Ulmestrand tested the grid, against 25 mm CL in most other areas. The majority of the loss found by Catchpole et al. (2006c) is thereby assumed to be small individuals that escape through the meshes of the 70 mm square-mesh codend.

In spite of the positive results in Swedish fisheries, Danish fishers have expressed concerns as to whether large *Nephrops* may be lost through the escape hole in front of the grid. In areas where these size groups are present, such a loss can have serious impact as prices are strongly size related. To meet this issue, a modified grid was designed and tested (Paper I). The bar spacing was increased to 80 mm in the upper quarter of the grid and to reduce the risk of larger fish passing between these bars, the guiding panel in front of the grid was removed (Fig. 9). To isolate the effect of the grid, the codend was made of 90 mm diamond-mesh netting identical to a standard codend with no grid that was tested in the same trial.

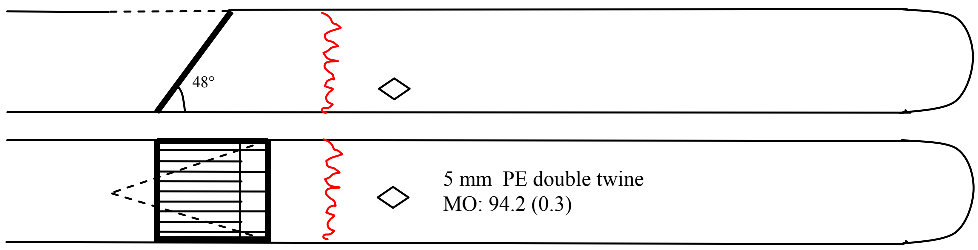

Fig. 9. A 90 mm diamond-mesh codend with the modified grid presented in Paper I. View from side and from top.

Despite the section with wider spacing between the bars, the resulting loss of marketable *Nephrops* (CL ≥ 40 mm) was 17 %. The loss was size dependent resulting in a loss of 41 % of individuals above 60 mm. With regards to fish, the grid dramatically reduced catches of all species above MLS most pronounced so for cod, haddock, saithe, and whiting. This indicates that the grid section with wider spacing did not induce more roundfish to have entered the codend even though most of them could morphologically pass through. However, up to 30 % of the round fish below the MLS that were estimated to enter the codend, passed between the bars and were subsequently retained by the diamond-mesh codend causing a high discard rate. These examples illustrates the importance and difficulties in adjusting a gear when two opposing selection processes (the selection curve of the grid is descending whereas that of the codend is ascending) are combined to retain all legal sized individuals of the target species – and nothing else.

The prospect of loosing marketable catch of *Nephrops* due to the grid is still of major concern and is an obstacle for implementation. Also, in many *Nephrops* directed fisheries, the by-catch of several fish species constitute an important part of the income and uncoupling the fishery for *Nephrops* from the by-catch of fish is therefore linked with marked reduction in income. Furthermore, criticism of the grids from the industry includes handling difficulties and blocking (Paper I; Catchpole et al., 2006c).

Square-mesh panels

Square-mesh panels (SMP's) are usually fitted in the upper panel of either the extension or the codend and the purpose is to add a section of open meshes to the diamond-mesh codend. The SMP's are particularly effective for species that exhibit distinctive upward escape reactions (Glass, 2000) and their use to reduce discards of roundfish in *Nephrops* trawls was initiated in 1990 (Arkley, 1990). The results for whiting and haddock were encouraging and since then, several experiments on SMP's in *Nephrops* trawls followed (e.g. Paper I; Briggs, 1992; Madsen et al., 1999; Krag et al., 2008). The effect of 90 mm and 120 mm SMP's on the escapement of cod below MLS has previously been found to be 33 % and 58 % respectively (Madsen et al., 1999; Krag et al., 2008). *Nephrops* have only been found to be affected by the panel if it is placed near the catch build-up or if the codend twist during fishing (Madsen et al., 1999; Krag et al., 2008). The efficiency of the panel is generally improved if it is moved towards the codline (Robertson and Shanks, 1994; Graham et al., 2003; Krag et al., 2008), if its mesh size is increased (Krag et al., 2008), and if diameter of twine is reduced (Revill et al., 2007). Furthermore, color of the netting has been shown to affect escape as fish are more likely to approach and penetrate meshes made of netting that is less visible i.e. presenting the lower contrast against the background (Glass et al., 1993; Glass, 2000).

In the study presented in Paper I, a 3 m long 120 mm SMP was inserted in the upper panel of the codend, 6 to 9 meters from the codline. This codend is in accordance with legislation (EC No. 51/2006) and at the time of the experiment a large proportion of the Danish fleet used it. Today it is mandatory in Kattegat. In this experiment the SMP was found to significantly reduce catches of haddock below MLS whereas no effect was found for cod and *Nephrops* and a negative effect was found for a narrow size range of plaice below MLS. The effect of the 120 mm SMP in the Danish *Nephrops* directed fishery is thus suggested to be marginal and, recently, the need to greatly reduce catches of cod above and below MLS has resulted in the development of new type of SMP with larger meshes and a more aft position (Madsen et al., 2010). Both parameters increase the risk of loss of *Nephrops* and the SMP is therefore placed in a four panel "sorting box" section inserted in the traditional two panel codend (Fig. 8).

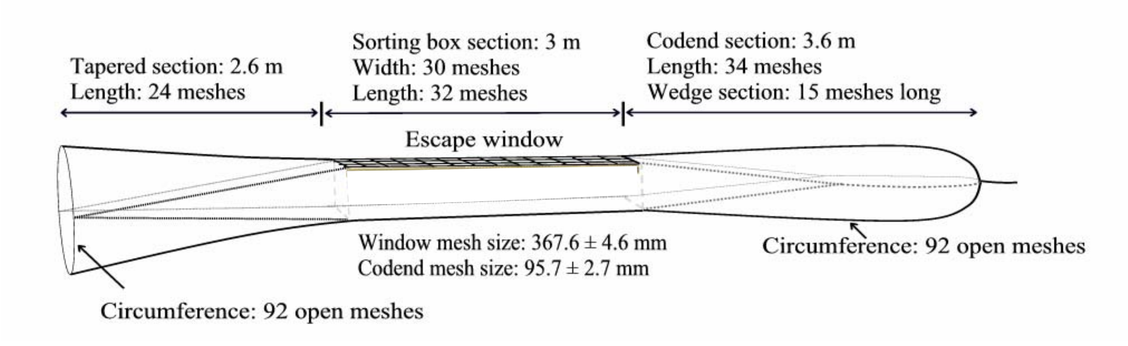

Fig. 8. The sorting box concept with a SMP in the top of a four panel section (Madsen et al., 2010).

This design stabilizes the codend and thus reduces the risk of twisting. Overall escape of all sizes of cod was estimated to be 92.5 % and for other round fish species escape was > 80 %. Furthermore, 83.5 % of the plaice escaped and so did 34 % of the marketable *Nephrops* (CL > 40 mm). The escape of *Nephrops* could be a consequence of the netting in the codend and not the SMP (Madsen et al., 2010).

The SMP's described above all aim at reducing catches of juvenile round fish without regarding discards of *Nephrops*. But as mentioned previously in this section, square meshes have also been found to improve size selectivity for *Nephrops* and they may therefore be used to reduce discards of undersized individuals. In the study presented in Paper IV, a codend was designed with the aim of improving size selection of *Nephrops* without increasing discards of neither cod nor plaice. In the previous experiments, *Nephrops* were found to escape almost exclusively through the lower panel (Paper III). And since the selection process was found to take place along the entire length of the codend (Paper II), the SMP was elongated to 5 m and inserted in the lower panel of a four-panel section (Fig. 3 in Paper IV). In the first of two experiments, a 70 mm SMP was tested. The netting of this SMP was similar to that of the plain two-panel square-mesh codend presented in Paper III. The mean estimates of

L_{50} obtained for cod and *Nephrops* in the codend with the 70mm SMP were comparable to those obtained in the plain square-mesh codend (Paper III) and higher than those of a plain two-panel diamond-mesh codend (Table 2).

		Cod		*Nephrops*		Plaice	
Codend	Year	L_{50}	*SR*	L_{50}	*SR*	L_{50}	*SR*
SMC70	2006	26.92	4.40	41.18	14.71	14.61	3.45
	2007	26.33	6.28	31.00	17.90	13.89	2.34
DMC90	2007	21.49	6.93	23.99	14.67	21.22	2.30
SMP70	2007	26.10	5.29	34.58	19.58	21.72	2.10

Table 2. Mean parameter estimates obtained for a 70 mm square-mesh codend (SMC70) (Paper III), a 90 mm diamond-mesh codend (DMC90) (Paper IV), and a 90 diamond-mesh codend with a 70 SMP (SMP70) (Paper IV). The SMC70 was tested both in 2006 and 2007.

Likewise, the estimate of *SR* for cod was identical to that in the 70 mm square-mesh codend while that for *Nephrops* was higher (Table 2). The selection estimates for plaice, however, were similar to those estimated for a 90 mm diamond-mesh codend constructed of the same netting as that used in the top and sides of this SMP codend (Paper IV) and better (i.e. higher L_{50} and lower *SR*) than that of the plain square-mesh codend. The experimental setup did not allow determination of whether the four-panel vs. two-panel construction contributed to the results. But despite difference in behaviour and morphology, size selectivity for all three species investigated, clearly benefited from combining netting in this four-panel construction as opposed to the two-panel codends composed of a single type of netting.

In both experiments (Paper III; IV), the 70 mm square meshes were thus found to have good size selective properties for *Nephrops*, but loss of legal sized catch was considerable (Paper III; IV). In the second of the two trials, the mesh size of the SMP was therefore reduced to 60 mm. For all three species, selection parameters of this codend were in between those of the plain diamond-mesh codend and the 70 mm SMP codend.

7.2. Management measures

As mentioned in section 2.2, the regulation of the fishery may in itself cause discard. Back in 1895, regulations on MLS were suggested as “the only practicable method of checking the depletion of the North Sea fishing grounds and enabling the fish supply to recover” (Holt, 1895) and it is often recommended, that the selectivity of the gear is to be adjusted for the L_{25} to equal the MLS for the species (Reeves et al., 1992). In multi-species fisheries where different species have different selection and different MLS, this is impossible and results in discard because of the severe mismatches between regulations on MMS and MLS (e.g. Paper I).

In the following, examples of alternative management measures with the primary aim on reducing discards are given.

7.2.1. Closed areas

Discarding can be controlled by closing areas where the composition of the catch is known to result in high discard rates. The closure can be permanent, temporary or managed in real time. Depending on the reason for the closure, some areas can be opened to fisheries that have a documented low catch of the species or sizes that needs protection as is the case for the Swedish grid in an area in Kattegat. The area is closed to protect spawning cod, and only gears with minimum catches of cod are allowed. Closing an area does not in itself reduce the fishing effort and the fleet might simply move to another location and resume fishing. The closed area therefore needs to cover a large proportion of what it is intended to protect (Catchpole et al., 2006b).

7.2.2. Restricting fishing time

The number of days-at-sea have been restricted in both Kattegat and Skagerrak and this reduces the volume of discards in proportion to fishing effort but at a substantial cost to the fishers (Catchpole et al., 2006b). The limitation encourage fishers to improve the catching efficiency of the gears in order to maximize landings. Fishing time restrictions should therefore be combined with regulation on the gears used. In Kattegat, days-at-sea have been unlimited if the “Swedish grid” was used and in this case, the restriction on fishing time was used as an incentive for fishers to adopt selective fishing techniques.

7.2.3. Adjusting the MLS

In principle, the size of the MLS is based upon an evaluation of the reproductive size of the species. In some cases, however, the MLS has an economic foundation. This is partly the case for *Nephrops* in Kattegat/Skagerrak where MLS is 40 mm carapax length in contrast to 25 mm in adjacent waters. The reason for this is uncertain but its maintenance is mainly founded on economic interests as legal landings of small

Nephrops may cause a drop in market prices of the larger sizes. However, it is also supported by studies of length at the onset of female sexual maturity in the area (Eggert and Ulmestrand 1999); a reduction in MLS will thus increase the fraction of females being landed without ever reproducing. This condition has been said to violate the precautionary approach (Myers and Mertz 1998) but it is only true if the females that are not landed, survive discarding. Reducing MLS to 25 mm and ensuring that no landable catch is discarded would largely solve the problem of discard of *Nephrops*. Under the assumption that a proportion of the *Nephrops* discarded will survive, reducing discards in this way will increase fishing mortality of the species unless the effort is proportionally reduced.

7.2.4. “No-discard” policy / utilizing discards

Discards may be theoretically eliminated by either banning them and / or by changing the market e.g. by using discards as animal feed or fishmeal. Banning discards i.e. introducing a “no-discard” regime has been pursued in a number of countries among which are Norway, Canada, the Faroes, Iceland, Ecuador, Peru, Namibia, South Africa, and the United States (Kelleher, 2005). This policy is essentially different from the “minimize-discard” policy that is used in the EU in that it shifts the focus from landings to gross catches and from production to total fishing mortality. Kelleher (2005) exemplifies this by the differences in Norwegian and EU legislation;

- Norway: “It is prohibited to catch…”
- EU: “It is prohibited to have on board…”

The choice for Norwegian fishers is therefore not whether to land or discard an organism but whether to catch it or not. The “no-discard” policy requires an active management regime where fisheries are closely monitored and areas with high by-catches need to be closed for fishery. This usually requires a high level of observer coverage as enforcement is considered to be difficult and some compensation for fishers for landing small fish is required. This could be through the elimination of MLS and subsequent creation of markets for incidental catches. This, however, may create the risk of small fish to become targeted. To be successful, an economic balance must be found that encourages compliance but does not increase fishing mortality (Catchpole et al., 2006b).

7.3. Summary of the technological means to reduce discards

In the multi-species *Nephrops* directed fisheries, the correlation between MMS and MLS is poor (Paper I; III; IV; ICES, 2004) and there is a general need to improve the selective characteristics of these fleets. In this section, a series of options have been listed that may reduce discards either by technological means or through management measures. In general, it is much easier to reduce or even eliminate discards in a single species fishery, whereas the reduction of discard in multi-species fisheries is more challenging.

It is not possible to substantially reduce discards of cod by use of traditional SMP's (e.g. 120 mm SMP in the extension) (Paper I). Larger mesh size in the panel can however reduce the catches of cod and haddock considerably (Madsen et al., 2010). To reduce the initial catch of a number of roundfish such as haddock and whiting, the design of the trawl could be adjusted to optimize catches of *Nephrops* by lowering the headline and shortening the sweeps. Finally a grid is very efficient in reducing catches of roundfish and flatfish (Paper I; Catchpole et al., 2006c; Valentinsson and Ulmestrand, 2008) and in combination with a 70 mm square-mesh codend, discards of juvenile roundfish are further reduced compared to a 90 mm diamond-mesh codend. The result is a clean *Nephrops* fishery but there are contrasting findings on whether or not the grid cause a loss of legal sized *Nephrops* (Paper I; Catchpole et al., 2006c; Valentinsson and Ulmestrand, 2008).

Size selectivity for *Nephrops* can also be improved without increasing discards of other species. By linking *Nephrops* morphology and mesh specifications, it was possible to simulate the selection process (Paper II). The simulations indicated that variation in mesh configuration with distance from the catch is a major contributor to *SR* and reducing this variation will sharpen the selection curve. Variation in mesh configuration is smaller in a square-mesh codend, which has also been found to have good selective properties for roundfish (Paper III). By exploiting knowledge on the preferred direction of escape (Paper III) and on optimization of mesh shape (e.g. Paper II) size selection of both *Nephrops*, plaice and cod could be improved by combining different mesh shapes in the codend (Paper IV).

7.3.1. Adaptation of selective gear by the industry

Species and size selection is not an exact process and the gear change is likely to reduce the revenue of the fishery. The prospect of a short term loss of landings of marketable fish is the most common reason that dissuades fishers from adopting new designs (Tschernij et al., 2004; Catchpole et al., 2005a; Jennings and Revill, 2007; Catchpole and Revill, 2008; Catchpole et al., 2008). Unless the fishermen are financially compensated for changing to the more selective gear, they are likely to change their behavior to minimize the economic loss; they might start to target fish that are more efficiently retained by the new gear, increase the effort to compensate for the loss, or make use of legal or illegal means to reduce the selectivity of the device (Krag et al., 2008). When evaluating the economic consequences of a change in gear, negative as well as positive contributions from all economically important species in the fishery should be included. Such an evaluation can help illuminate the incentive required to implement effective measures. In the case of the Danish *Nephrops* fishery, such incentives have been additional days-at-sea and access to areas that are otherwise closed to fishery. These incentives have not been sufficient for the Danish fishermen to adopt the "Swedish grid" which may be a consequence of the extra costs as well as precaution associated with changing gear, and reluctance towards engaging in several management regimes.

The problem of discards is not solved by managers or scientists alone. Fishermen and the fishing industry have a unique practical knowledge of fishing gear, fishing grounds, and economic realities within a fishery. Their input is vital if long term cost effective solutions are to be developed (Glass, 2000).

8. Final remarks and future work

As the present work documents, it is technologically possible to substantially reduce discards in the Danish *Nephrops* directed fishery. In most cases, however, it will be at the expense of marketable catch and with no reduction in impact on the bottom. Trawling has been shown to have a negative impact on the biomass, production, and species richness of benthic communities and the effect is positively related to trawling intensity (Kaiser et al., 2002; Tillin et al., 2006; Shephard et al. 2010). If trawling intensity is increased as a consequence of the introduction of a more selective but less efficient gear, the environmental effect is therefore counteractive and should be evaluated.

Alternative fishing methods such as creeling should also be evaluated and further developed as these may prove to be economically viable to a niche of vessels while the effort of trawling could be reduced. In a life cycle assessment, creeling was found to lead to considerably lower discard, fuel use and seafloor impact (Ziegler.F. and Valentinsson, 2008) than the conventional trawling.

The Danish *Nephrops* directed fishery may be comparable to many other mixed-species fisheries but the solution to the discard problem will vary among fisheries and regions. A device or fishing method that is efficient in one area will not necessarily be efficient in other areas.

Selective gears are only efficient in reducing discard if their implementation is aligned with other management measures regulating the fishery. A shift in the management regime towards regulating catches instead of landings will support the development of more selective fisheries.

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Paper I

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Evaluation of three levels of selective devices relevant to management of the Danish Kattegat–Skagerrak *Nephrops* fishery

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ABSTRACT

This study illuminates a range of technological options relevant to present legislation for regulating fish by-catch in a small-meshed *Nephrops* fishery. The selection of cod, haddock, hake, lemon sole, *Nephrops*, plaice, saithe, witch, and whiting were evaluated using the twin-trawl technique for: (i) a 90 mm diamond mesh codend (standard codend); (ii) a standard codend with a 120 mm square mesh panel (SMP); and (iii) a standard codend with a 35/80 mm grid mounted in the extension piece to hinder access to the codend for large individuals. We used selection models to estimate selection parameters by species and confidence bands to compare the selective properties of different gear types. For cod, haddock, hake, *Nephrops*, plaice, and whiting we obtained estimates for all three gear variants, whereas we obtained estimates for lemon sole and witch only with the standard and the SMP codends and for saithe only for the SMP codend. The SMP significantly ($p < 0.05$) improved selectivity of haddock in terms of releasing more individuals below minimum landing size (MLS). For a narrow size range of plaice below MLS, the SMP retained more individuals than did the standard codend. No effect of the SMP was detected for any of the other species. The grid codend significantly reduced catches of all fish species above MLS, but the codend also had an increased retention of cod and haddock below MLS. Furthermore, the grid resulted in a 17% loss of marketable *Nephrops*.

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1. Introduction

Nephrops (*Nephrops norvegicus*) is the most valuable commercial species in Kattegat and Skagerrak. The fishery for *Nephrops* is a mixed species fishery, and by-catch of other species constitutes an important part of the income (Krag et al., 2008). Compared to the white fish fishery (e.g., in the North Sea), the bottom trawls used for catching *Nephrops* have relatively small meshes (90 mm full mesh), and the discard rates of commercial fish species as well as undersized *Nephrops* are high (Krag et al., 2008). According to ICES (International Council for the Exploration of the Seas), the stock of Atlantic cod (*Gadus morhua*) is at a critically low level and special attention is paid to the discard of this species. In current legislation, the minimum allowed mesh size in this fishery is 90 mm. A 120 mm square mesh panel (SMP) was introduced as an option in the legislation, and since 2004 its use has been rewarded with extra days at sea (Krag et al., 2008). To uncouple the fishery for *Nephrops* from the by-catch of fish, in particular cod, a sorting grid was introduced in legislation in 2005. The resulting gear is highly selective (Valentinsson and Ulmestrand, 2008), and its use is rewarded by unlimited number of days at sea. The properties of both the SMP and the grid have been investigated in a number of comparative selectivity experiments (Catchpole et al., 2006; Krag et al., 2008; Valentinsson and Ulmestrand, 2008). However, the experimental setup used in those investigations only allows estimation of the relative selectivity of the gear and results will be somewhat depending on size distributions of the fish and *Nephrops* encountering the gear. The present study provides estimates on the absolute selectivity, which can be used to compare the selectivity of all sizes of fish and *Nephrops* in the tested gears. In addition, prior to this study, no selectivity estimates were available for several of the species targeted in this fishery.

The gears tested in this study represent three levels of regulating fish by-catch and discard. The standard codend is expected to have a high level of both fish by-catch and discard but a low loss of commercial catch. Use of a standard codend with a 120 mm SMP is expected to reduce the discard with no or limited effect on the commercial catches. The very selective grid device is expected to have a low level of both by-catch and discard but the loss of commercial species and sizes is expected to be high. We modified the grid

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specified in the legislation to improve retention of larger *Nephrops*. This fraction of the catch has a high commercial value, and its retention is therefore an important issue if the grid concept is to be accepted by the industry. We used the standard 90 mm diamond mesh codend in combination with the grid in order to isolate its effect on discard and by-catch. In current legislation, the grid may only be used in conjunction with a 70 mm square mesh codend.

2. Methods

2.1. Experimental methods

We tested the three codends in paired gear experiments (Wileman et al., 1996) using a 40 mm control codend. Compared to the covered codend technique (Wileman et al., 1996), which also allows assessment of the absolute selection parameters, the paired gear technique is relevant when working on small vessels where a codend cover is difficult to handle and may slow down the haul-back of the gear. This may cause the proportion of individuals escaping the codend at the sea surface to be higher than under commercial conditions (Madsen et al., 2008). To avoid bias due to spatial and temporal heterogeneity as well as differences in performance between starboard and port side trawls, all three gear types were tested throughout the trial and codends were changed every second day.

2.2. Sea trials

In September and October 2005, we conducted a 3-week trial in Skagerrak and Kattegat aboard a 50 BRT commercial fishing vessel, the FN234 *Canopus*. *Canopus* is a twin-trawler rigged for *Nephrops* fishing in the investigated areas. The trawls are combined fish and *Nephrops* trawls with a nominal mesh size of 80 mm and 400 meshes in circumference. A three warp towing system with a 650 kg roller clump and 194 cm *Dangren* otter boards, was used to tow the gear. The towing rig behind the otter boards consisted of 101 m sweeps. Average distance between doors was 98 m and rubber cookies made up the ground gear. Choice of fishing grounds was based on the expected catch distribution of the primary target species: *Nephrops*, cod, and plaice (*Pleuronectes platessa*).

2.3. Experimental codends

The codends tested were: (i) a standard codend; (ii) a standard codend with a 120 mm (SMP) in the extension piece; and (iii) a standard codend with a 35/80 mm grid in the extension piece (Fig. 1). The same standard codend was used in all gears. It was constructed of two panels of 90 mm nominal diamond mesh and had 92 open meshes around (Fig. 1, standard codend). A large portion of the Danish fishing fleet uses this type of codend. The SMP codend meets the requirements specified in the legislation (Council Regulation (EC) No 51/2006, app. 1 to annex IIA) (Fig. 1, SMP codend).

The Danish Fishermen's Association raised concerns about possible loss of marketable *Nephrops* caused by the grid specified in the legislation (Council Regulation (EC) No 51/2006, app. 2 to annex III). We therefore made changes in the gear with the aim of retaining a higher proportion of the legal-sized *Nephrops* without compromising the escapement of roundfish. We maintained a distance of 35 mm between the bars in the lower three-quarters of the grid but increased the bar spacing to 80 mm in the upper quarter (Fig. 1, grid details). The prototype grid used in this experiment was made of stainless steel and weighed ~30 kg. The grid was inserted in a four panel section of the extension piece, and an escape hole was cut in the top panel in front of the grid. A separate bag (nominal mesh opening = 40 mm) collected the catch that passed the 80 mm section of the grid. We refer to this collection bag as Test 2 and the main codend as Test 1 (Fig. 1, grid codend).

For all gear types, we measured mesh opening of the nettings and bar spacing of the grid 50 times before (dry condition) and after (wet condition) the trials and then averaged them (Fig. 1). All measurements were taken with a 4 kg spring-loaded ICES gauge (Wileman et al., 1996). Equivalent values for the EU wedge with a 5 kg hanging weight would be approximately 4% higher (Ferro and Xu, 1996); for the Omega wedge (Fonteyne et al., 2007) at 125 N, measurements would be approximately 3.7% higher (our own unpublished data for dry double P.E. netting).

2.4. Measurements of the catch

The total length of commercially important species in the catch was measured to the centimetre below for fish (cod, haddock (*Melanogrammus aeglefinus*), hake (*Merluccius merluccius*), lemon sole (*Microstomus kitt*), plaice, saithe (*Pollachius virens*), witch (*Glyptocephalus cynoglossus*), and whiting (*Merlangius merlangus*)) and the carapace length (CL) was measured to the millimetre below for *Nephrops*. We used the midpoints of the length classes in the analyses. In most cases, the entire catch of all commercially important species was measured, but large sub-sampling fractions (14–75%) were taken in hauls where the numbers were high. The catch of non-commercial species and debris was only weighed. Weights of the measured fish species were estimated using monthly specific conversion factors from Coull et al. (1989), and sex-specific conversion factors were used for *Nephrops* (ICES, 1995). Wind speed and towing speed were recorded when the gear was deployed and depth was recorded every tenth minute.

2.5. Selectivity model for the standard and SMP codend

Data from experiments with various codends tested in a paired gear experimental design are commonly analysed using a mixed model approach. Such approaches include a commonly used two-stage process (Fryer, 1991; Millar and Fryer, 1999) as well as more coherent analyses using, for example, SAS PROC NLMIXED (Millar et al., 2004). Data were however not amenable to any of these methods, due to lack of convergence. An analysis based on data combined by stacking data from all hauls was therefore considered more viable. The estimates obtained from this analysis are similar to those obtained using pooled data. The model induces over-dispersion because it neglects the haul sampling structure of the hauls. Replicate hauls allow for calculating the REP statistic based on the Pearson estimator of dispersion (McCullagh and Nelder, 1989, p. 127). The covariance matrix for the parameter estimates is subsequently adjusted by the REP statistic (Millar et al., 2004). Estimates obtained by pooling or stacking data differ conceptually from those obtained from mixed effects models, including the two-stage approach. Mixed effects models provide the expected selectivity for single hauls, whereas the parameters of the combined hauls approach (i.e., analyses of stacked or pooled data) provide the expected selectivity pattern across the population of all hauls.

2.6. Selectivity model for the grid codend

The effective selection in the codend mounted with a grid results from two counter-oriented processes: an absorption through the grid followed by a retention by the codend. Therefore, we assume that the resulting selectivity curve will be concave or convex (i.e. bell- or bowl-shaped), with one leg given by a descending sigmoid curve (representing grid absorption) and the second leg given by an ascending sigmoid curve (representing codend retention).

If $r_g(\ell)$ and $r_c(\ell)$ denote the conditional probability for a length ℓ fish to be retained by the grid and the codend, respectively, given

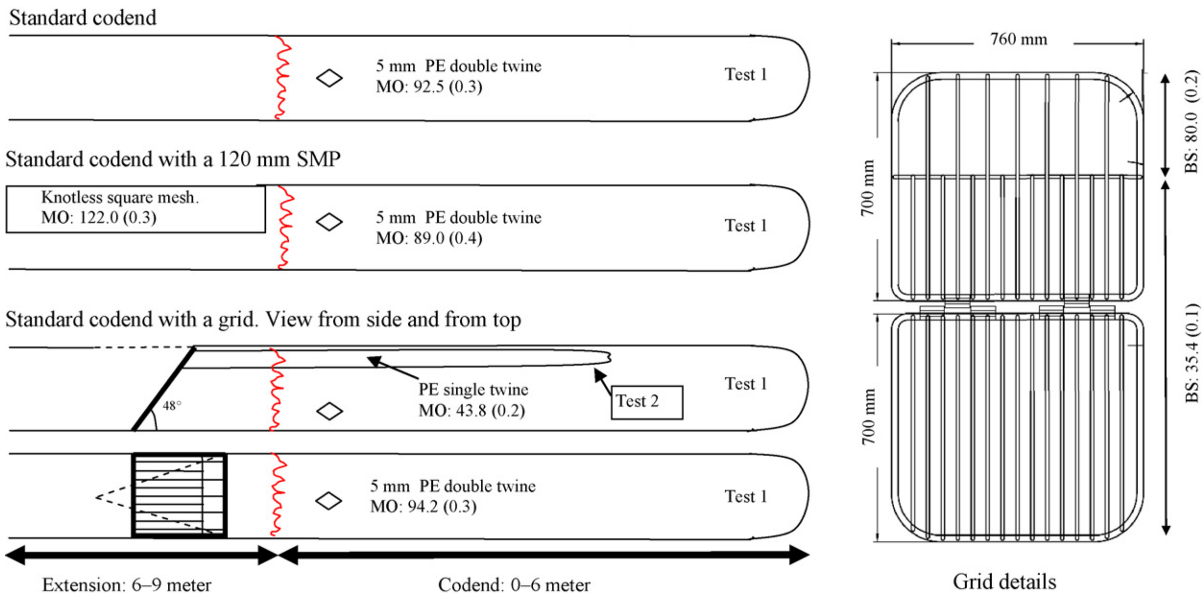

Fig. 1. Drawings of the three codends and details of the grid. Mesh openings (MO) and bar spacings (BS) are in mm. Standard errors are shown in brackets.

that it has encountered the device, then the effective selectivity $r_{eff}(\ell)$ (i.e., the conditional probability that a length ℓ fish passes through the grid and is retained by the codend given it has entered the codend) is given by:

$$r_{eff}(\ell) = [1 - r_g(\ell)] \cdot r_c(\ell).$$

The assumption of the bell-shaped form of $r_{eff}(\cdot)$ allows a more parsimonious and robust approach to modelling the selectivity. For most purposes, $r_{eff}(\cdot)$ can be approximated by a scaled two-parameter density function reducing the total number of parameters to three:

$$r_{eff}(\ell) \approx \tilde{r}_{eff}(\ell; \boldsymbol{\theta}) = \omega \cdot f(\ell; \boldsymbol{\beta}),$$

where $\boldsymbol{\theta} = (\omega, \boldsymbol{\beta}^T)^T$, ω is a scaling parameter giving the maximum retention probability, and f is a density function scaled to unit height and parameterized by $\boldsymbol{\beta}$. It is convenient to name the $\tilde{r}_{eff}(\cdot; \boldsymbol{\theta})$ curves by the density having the same functional form. Table A1 lists three curves derived from a normal, a log-normal, and a gamma density. The three curves represent a range of different shapes, which are sufficiently versatile for most needs. Furthermore they can be written in log-linear form:

$$\log(\tilde{r}_{eff}(\ell; \boldsymbol{\theta})) = \beta_0 + \beta_1 \cdot f_1(\ell) + \beta_2 \cdot f_2(\ell),$$

where $f_1(\ell)$ and $f_2(\ell)$ are parameter-free functions of ℓ. Expressed in terms of $\tilde{r}_{eff}(\ell; \boldsymbol{\theta})$ the expected proportion of length ℓ fish caught in the test codend becomes:

$$\begin{aligned}\phi(\ell) &= \frac{p \cdot \tilde{r}_{eff}(\ell; \boldsymbol{\theta})}{1 - p + p \cdot \tilde{r}_{eff}(\ell; \boldsymbol{\theta})} \\ &= \frac{p \cdot \omega \cdot f(\ell; \boldsymbol{\beta})}{1 - p + p \cdot \omega \cdot f(\ell; \boldsymbol{\beta})} \\ &= \frac{\pi \cdot \omega \cdot f(\ell; \boldsymbol{\beta})}{1 + \pi \cdot \omega \cdot f(\ell; \boldsymbol{\beta})} \\ &= \frac{\exp[\tilde{\beta}_0 + \beta_1 \cdot f_1(\ell) + \beta_2 \cdot f_2(\ell)]}{1 + \exp[\tilde{\beta}_0 + \beta_1 \cdot f_1(\ell) + \beta_2 \cdot f_2(\ell)]},\end{aligned}$$

where p denotes the split parameter (i.e., the efficiency of the test trawl relative to that of the control), $\pi = p/(1-p)$, and $\tilde{\beta}_0 = \beta_0 + \log \pi$. Because p and ω are confounded in $\tilde{\beta}_0$, further inference about the efficiency (ω) is therefore subject to assumptions about p. Although previous experiments have shown that the split may vary considerably from haul to haul, it is appropriate to assume a mean value of 50%. Under this assumption we get:

$$\mathrm{logit}(\phi(\ell; \boldsymbol{\theta})) = \beta_0 + \beta_1 \cdot f_1(\ell) + \beta_2 \cdot f_2(\ell),$$

and we may therefore estimate the model using standard generalized linear model GLM tools for binary data. Table A2 gives the modal length ℓ_0, the spread σ, and the modal value ω of the selection curves expressed in terms of the β parameters. Estimated models can be assessed using conventional goodness-of-fit tools, including residual plots. Selection of functional form can appropriately be addressed using an Akaikes Information Criterion (AIC) (Akaike, 1974). In cases of sub-sampling, data were scaled up prior to combining the data. As for the standard and the SMP codends, the variance estimates were adjusted by the REP statistic.

The model does not account for the catch in the upper quarter of the grid. Selectivity parameter estimates for the grid are thus based on the lower three quarters of the grid and does only apply to this part. It had a bar distance of 35 mm and corresponds to the catch in Test 1 (Fig. 1, grid codend). We assessed the effect of introducing the upper quarter using a simple comparison of the relative catches above and below MLS.

2.7. Comparison of the selective properties of the different gears

We compared the three gears by checking for overlap of the approximate 95% confidence bands for the different selection curves. In this way we could compare the selectivities for all length classes. The approximate 95% confidence bands were based on 2 standard error (s.e.) limits. In the stacked data sets, the degrees of freedom are high (>60) and 2 standard error limits therefore provides a conservative approach.

3. Results

3.1. Operational conditions

We conducted a total of 58 hauls: 18 with the standard codend, 18 with the SMP codend, and 22 with the grid codend (Fig. 2). Table 1 lists the average values for the operational conditions. Mean catches in the fine-meshed control codends were 22–23% higher in

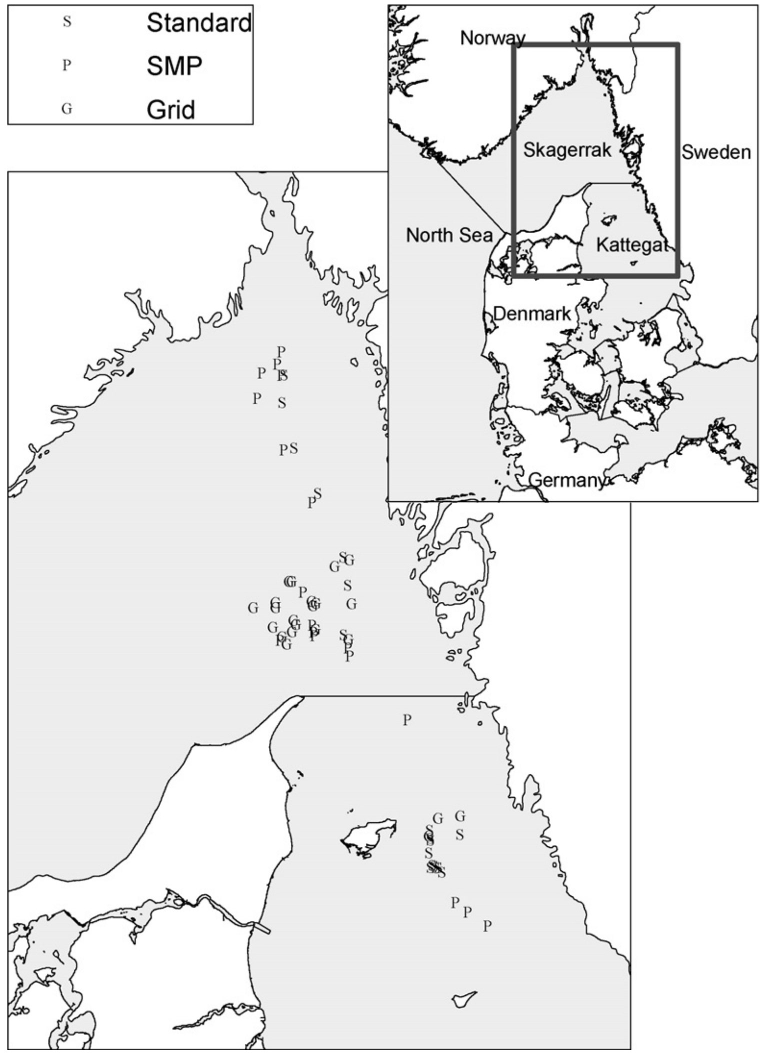

Fig. 2. Distribution of hauls using the three different gear types.

hauls testing the standard codend. Because the selective devices sort out part of the incoming fish, the mean catch weight in the test codends was 37% lower for the SMP codend and 89% lower for the grid codend compared to the mean catch weight for the standard codend (Table 1). During the experiment, average shrinkage of the 90 mm netting used in the standard codends ranged from 2.5–5.4%.

3.2. Catches

High numbers of cod, *Nephrops*, and whiting above and below MLS were caught in all three experiments (Table 2). Catch composition showed high variation and in areas with large catches of plaice (e.g., in the Southern part of Kattegat) catches of *Nephrops* were low and vice versa. At the time of the experiment, the length separation between age classes of all gadoids resulted in low numbers of fish at lengths around 20 cm and 35 cm (Fig. 3). The length distribution of witch showed the same tendency, whereas the age structure was unclear for lemon sole, plaice, and *Nephrops* (Fig. 3). Only large saithe (>35 cm) were present in this study.

3.3. Estimation of selection parameters

Size distributions of most species investigated in this experiment were characterized by pronounced age classes, which resulted in relatively few individuals in the selective range of the gears tested. By stacking data, we were able to estimate parameters for eight species in the standard codend, nine in the SMP codend, and six in the grid codend (Table 3). The resulting standard errors for the estimates of L_{50} (Length at 50 % retention) and for $SR = (L_{75} - L_{25})$ were relatively high, particularly for the SMP codend. *Nephrops* in the SMP codend did not converge when the analysis was run with default settings, so we increased tolerance from 1E−12 to 1E−4. All

Table 1
Average (Avg.) values and standard error (s.e.) for the operational conditions. For the grid codend, only catch weight from Test 1 is shown.

	Wind speed (m/s)		Haul duration (min)		Ground speed (kts)		Depth (m)		Catch weight, test (kg)		Catch weight, control (kg)	
	Avg.	s.e.	Avg.	s.e.	Avg.	s.e.	Avg.	s.e.	Avg.	s.e.	Avg.	s.e.
Standard	5.4	3.2	102	15	2.52	0.06	97.1	32.2	393	367	534	426
SMP	7.3	3.8	115	11	2.52	0.08	127.1	49.1	248	182	416	388
Grid	6.9	3.5	115	10	2.45	0.11	144.0	47.0	43	27	410	420

Table 2
Total scaled up number of fish and *Nephrops* caught in the experiment. Catch is divided into fractions above and below the MLS, and length is total length (cm) for fish and carapace length (mm) for *Nephrops*. There is no MLS for witch. For *Nephrops*, both the Kattegat–Skagerrak MLS (40 mm) and the European MLS (25 mm) are shown. Test 1 is the 90 mm codend, which collects the entire catch in the standard and the SMP codends as well as the catch behind the lower three-quarters of the grid. Test 2 is a fine-meshed collection bag that collects the catch behind the upper quarter of the grid.

	Length range	Standard		SMP		Grid		
		Control	Test 1	Control	Test 1	Control	Test 1	Test 2
Cod	≥30 cm	3172	3283	1485	1305	2130	18	50
	<30 cm	2337	233	2893	259	2163	133	538
Haddock	≥27 cm	534	456	1504	300	324	8	2
	<27 cm	2620	369	5054	147	1308	134	88
Hake	≥30 cm	72	57	136	72	193	24	28
	<30 cm	294	128	252	151	421	157	66
Lemon sole	≥26 cm	149	144	79	87	67	8	6
	<26cm	281	77	159	68	83	15	11
Nephrops	≥40 mm	3235	3124	1942	1860	3647	2473	570
	<40 mm	5224	4078	2529	2154	7171	5888	488
	≥25 mm	8365	7149	4442	4002	10702	8327	1054
	<25 mm	94	53	29	12	116	34	4
Plaice	≥27 cm	703	908	662	703	108	9	4
	<27 cm	838	747	445	433	189	44	24
Saithe	≥30 cm	333	339	539	356	1628	0	1
	<30 cm	1	0	1	0	0	0	0
Witch	Total	593	372	767	526	650	117	112
Whiting	≥23 cm	4047	1649	2246	221	1761	56	25
	<23 cm	16138	384	3691	111	2835	53	156

other species converged with the low level of tolerance. Although a tolerance level of 1E−4 is not of concern by itself, the need to increase it from 1E−12 indicates that there might be problems with the fit.

For the standard codend, the range of estimated L_{50}s for all fish species studied was surprisingly narrow: 21.9 to 26.1 cm. For the SMP codend, estimates of L_{50}s ranged from 18.2 to 43.8 cm. The increase in range reflects that some species actively escape through the SMP and thereby obtain a higher L_{50}. The estimated L_{50}s of the remaining species were low compared to the standard codend. In our study, this result might be a consequence of the generally lower catch weights in the SMP codend (Table 1).

Except for whiting, the estimated L_{50}s for all species in the standard codend were lower than the current MLS (see Length range column of Table 2). The actual effect on discard of a mismatch between regulations on MLS and on minimum mesh size, depends on the size structure of the population. But decreasing the discrepancy between MLS and L_{50} will reduce the risk of discard.

For the grid codend, data from the lower three-quarters of the grid for cod, haddock, hake, *Nephrops*, plaice, and whiting could be fitted to one of the three bell-shaped curves tested (Table 3, Fig. 4). Max retention of *Nephrops* ($\hat{\omega} = 88\%$) was at 35.5 mm.

3.4. Effect of the grid on catches above and below MLS

The grid tested in this experiment drastically reduced catches of all fish species above MLS (Table 2). This effect was most pronounced for cod, haddock, plaice, saithe, and whiting. During the 22 hauls, a total of only 116 fish above MLS were caught behind the 80 mm portion of the grid (Table 2). With the grid, 17% fewer *Nephrops* above the Kattegat/Skagerrak MLS were caught in the test codends (Test 1 + Test 2) compared to the fine-mesh control codend. The loss of *Nephrops* was size dependent, i.e., loss of individuals with CL ranging from 40–45 mm was 8% and loss of individuals with CL ≥ 60 mm was 41%. For comparison, there was a 6% loss of individuals with CL ranging from 40–45 mm in the standard codend, hence loss of this size group caused by the grid was relatively small. The larger the *Nephrops*, the smaller the loss through the meshes of the standard codend; thus the majority of the loss of these size groups can be attributed to the grid. The fraction of retained *Nephrops* entering the codend through the 80 mm bar spacing is likewise size dependent and increases gradually from 14% (CL = 40–45 mm) to 60% (CL ≥ 60 mm).

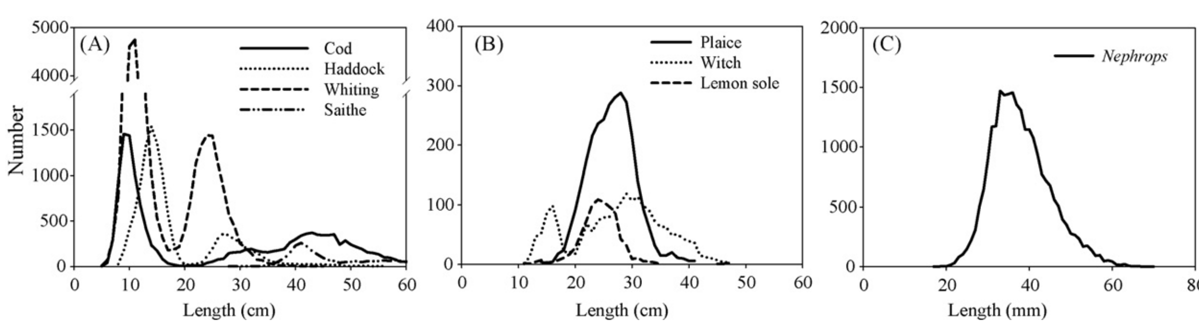

Fig. 3. Length distribution of gadoids (A), flatfish (B), and *Nephrops* (C). Distributions are based on scaled up numbers of pooled data from the fine meshed control codends of all hauls.

Table 3
Estimates (Est.) and standard error (s.e.) of selection parameters for all experimental codends. Goodness of fit is indicated by deviance (dev.) and degrees of freedom (dof). N.a. indicates that the analysis did not converge for the species. *SF* estimates are based on measured mesh openings converted to the EU wedge.

	Standard codend						
	L_{50} (cm)		*SR* (cm)		*SF*	dev.	dof
	Est.	s.e.	Est.	s.e.			
Cod	23.02	1.28	6.97	0.80	2.39	1189	811
Haddock	22.91	1.43	7.41	0.89	2.38	501	367
Hake	22.31	4.03	10.89	7.01	2.32	268	184
Lemon sole	25.80	1.35	3.81	1.09	2.68	189	184
Nephrops[a]	27.08	0.94	12.29	2.49	0.28	756	565
Plaice	21.91	0.33	2.49	0.70	2.28	350	271
Saithe	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Whiting	26.10	1.29	7.39	0.49	2.71	1215	413
Witch	25.97	1.78	8.59	1.57	2.70	364	266

	SMP codend						
	L_{50} (cm)		*SR* (cm)		*SF*	dev.	dof
	Est.	s.e.	Est.	s.e.			
Cod	27.05	1.31	10.93	0.91	2.92	1021	723
Haddock	43.80	7.24	18.56	2.18	4.73	498	286
Hake	18.23	2.39	5.04	3.74	1.97	280	217
Lemon sole	29.57	6.54	7.35	2.86	3.19	102	92
Nephrops[a]	23.58	1.96	3.58	7.20	0.25	646	494
Plaice	18.79	1.27	5.11	2.25	2.03	325	222
Saithe	37.10	0.61	1.75	1.04	4.00	356	232
Whiting	34.50	12.17	15.54	3.55	3.73	472	266
Witch	23.74	2.69	12.08	3.13	2.56	474	348

	Grid codend							
	ℓ_0 (cm)		σ (cm)		ω		dev.	dof
	Est.	s.e.	Est.	s.e.	Est.	s.e.		
Cod	19.63	0.38	5.32	0.34	0.44	0.09	440	632
Haddock	16.26	0.66	5.56	0.77	0.15	0.02	237	281
Hake	21.51	1.91	7.97	1.46	0.42	0.04	204	251
Lemon sole	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Nephrops[a]	35.48	0.45	14.67	1.00	0.88	0.02	1082	638
Plaice	21.49	1.19	5.87	0.88	0.25	0.03	73	108
Saithe	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Whiting	22.37	2.93	19.02	10.76	0.03	1.13	263	315
Witch	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

[a] Unit for *Nephrops* is mm.

3.5. Comparison of the selection curves for the three gear types

Approximate 95% confidence bands (2s.e.) were plotted to compare selectivity among the three gear types (Fig. 5).

Haddock was the only species for which insertion of the SMP significantly ($p < 0.05$) reduced retention for a larger size range (18.9–53 cm) of individuals. In the 16.7–20.7 cm size range, retention of plaice was significantly ($p < 0.05$) increased by the SMP.

Compared to the standard codend, the codend with a grid had a significantly ($p < 0.05$) lower retention of large cod, haddock, whiting and plaice (longer than 25, 20, 17 and 22 cm, respectively) and a significantly ($p > 0.05$) higher retention of small cod and haddock (ranging from 10–19 and 11–15 cm, respectively). Retention of *Nephrops* longer than 41.8 mm was significantly lower ($p < 0.05$) in the grid codend than in the standard codend.

4. Discussion

Although the 90 mm standard codend commonly used in the Kattegat–Skagerrak *Nephrops* fishery is known to be not very selective, this is the first attempt to estimate the absolute selectivity of several species in this gear. Our results clearly demonstrate that selectivity in the standard codend is inadequate, and its use results in high discard rates for all of the main species in the fishery studied.

Action is needed to reduce the discard in this fishery, and technological improvements might solve a major part of the problem. Previous investigations (Krag et al., 2008) have shown that the straightforward solution to reducing discard of a gear by increasing the codend mesh size can lead to severe losses of catches of *Nephrops*. Thus, selective devices in which retention of legal sized *Nephrops* is unaffected while selection of other species is improved are preferable.

4.1. Estimates of selectivity

The present experiment provided estimates of selectivity parameters for all commercially important species in the *Nephrops* fishery. For hake, lemon sole, plaice, and witch, no published selection estimates were available for comparable gear types (otter trawl with mesh sizes above 60 mm) prior to this study.

Selection factors ($SF = L_{50}$/mesh size (EU wedge)) often are used to compare results with previous findings. In the standard codend, cod, haddock, and whiting had estimated *SF*s of 2.4, 2.4, and 2.7, respectively (Table 3). These values are comparable to the relatively wide range of *SF* estimates reported in previous experiments (cod: 2.5–4.1; haddock: 1.7–3.7; whiting: 2.4–4.2) (Halliday et al., 1999; Madsen et al., 1999; Graham and Kynoch, 2001; Graham et al., 2003, 2004; Kynoch et al., 2004; Madsen and Stæhr, 2005; O'Neill et al., 2006).

However, the estimated *SF* for *Nephrops* (0.28) was lower than published values from experiments in the same area (0.37–0.51) (Kirkegaard et al., 1989; Larsvik and Ulmestrand, 1992; Madsen et al., 1999). Differences in twine thickness, which has been documented to affect selectivity for fish (e.g., Herrmann and O'Neill, 2006; Sala et al., 2007), may explain the low *SF* for *Nephrops*. In the three comparable experiments (Kirkegaard et al., 1989; Larsvik and Ulmestrand, 1992; Madsen et al., 1999), the codends were made of 2.5 mm double twine or 2–3 mm single twine, whereas the netting in the present experiment was made of 5 mm double twine.

4.2. Improving selectivity by using a square mesh panel

SMPs fitted in a diamond mesh codend improve the selectivity of round fish and, in particular, the selection of haddock and whiting benefits from this device (e.g., Madsen et al., 1999; Graham et al., 2003; O'Neill et al., 2006; Revill et al., 2007). Both mesh size of the

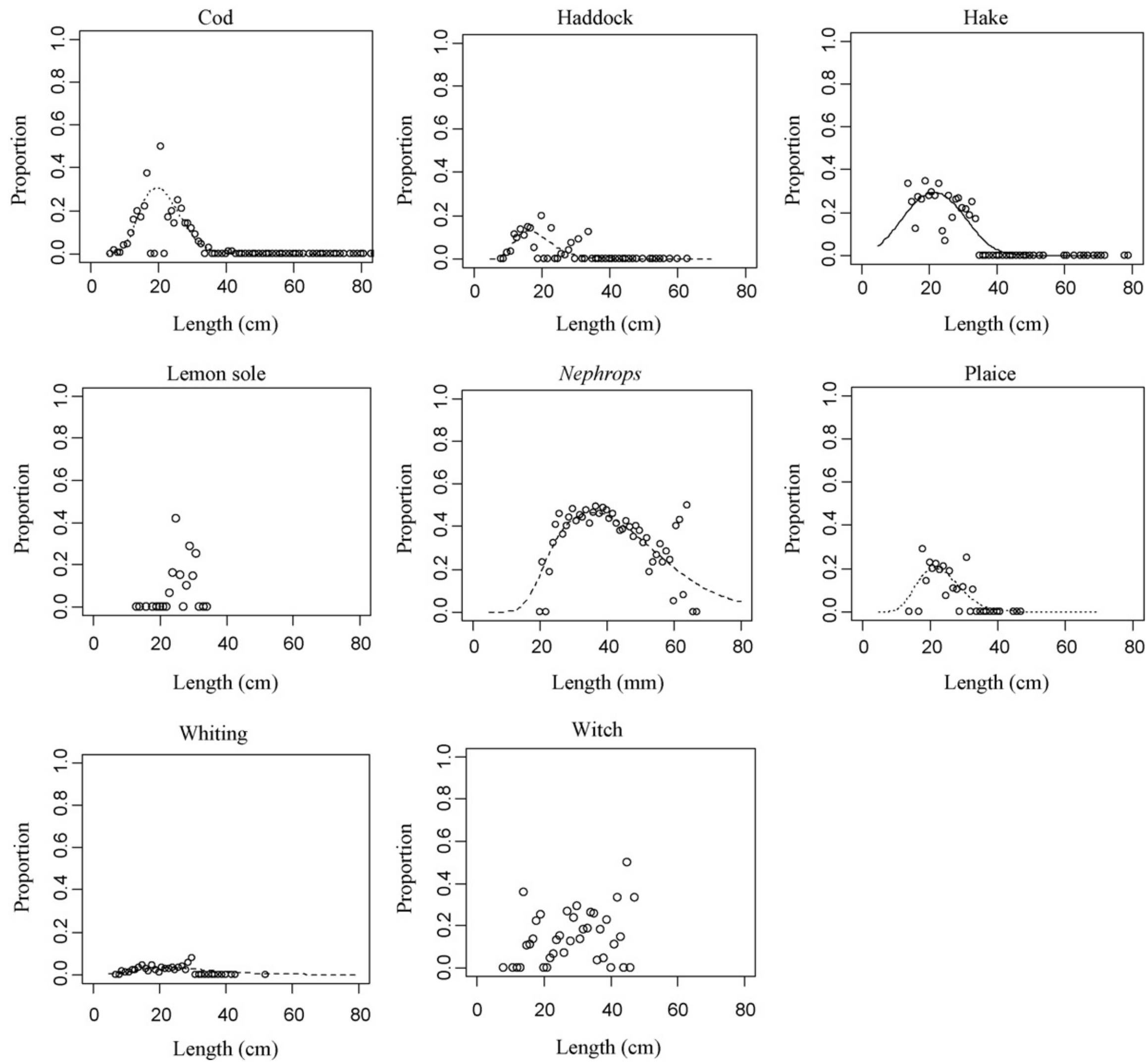

Fig. 4. The observed proportion of catch retained in the test codend; (Test 1/(control + Test 1)) based on pooled data for all hauls testing the grid codend. Only catches behind the lower three-quarters of the grid (bar distance = 35 mm) are included. The bell-shaped GLM model with the best fit is shown as a line: solid line = "Normal"; hatched line = "Log-normal"; and dotted line = "Gamma". Data for lemon sole, and witch could not be fitted to any of the tested models.

SMP and its position within the codend influence its ability to sort out undersized round fish (e.g., Robertson and Shanks, 1994; Krag et al., 2008). This experiment is the first that allows estimation of absolute selectivity of the 120 mm SMP implemented in legislation.

Estimated L_{50} for haddock was significantly ($p < 0.05$) higher in the SMP codend than in the standard codend, whereas any effect on whiting was masked by low catches of large individuals, which resulted in a high variance of the selection parameters. For cod, results marginally indicated that the SMP increased estimates of both L_{50} and *SR*, but the effect was not significant. Madsen et al. (1999) estimated selectivity parameters of cod in gears with SMPs in the aft end of the codend, and they found no significant effect on either L_{50} or *SR*. However, the same study found catches of cod below MLS to be significantly reduced by the SMP. In a catch comparison experiment of a comparable SMP, Krag et al. (2008) reported no effect on the catches of cod.

SMPs have previously been reported either not to affect catches of flatfish (e.g., Madsen et al., 2006) or to reduce retention of small plaice (Revill et al., 2007). The reason for the significant increase in retention of a narrow size range (16.7–20.7 cm) of plaice in this study is unknown. For hake, *Nephrops*, and saithe, the variance of the *SR* estimates was very high, thus the actual values of the parameters are uncertain. For the remaining species (cod, haddock, lemon sole, plaice, whiting, and witch), the relative increase in *SR* between the standard and the SMP codends exceeded the change in L_{50}. This might be an artifact caused by the fact that total selection of the codend (i.e., codend + SMP) was fitted to one logistic curve despite a possible difference in L_{50} between the two components. Investigation of plots of pooled data did not reveal any indication of this in this study, but O'Neill et al. (2006) detected two independent L_{50}s for haddock for a 90 mm SMP in a 100 mm diamond mesh codend.

4.3. Improving selectivity by use of a grid

The grid dramatically reduced catches of all fish species above MLS, and the effect was most pronounced for cod, haddock, plaice, saithe, and whiting. These findings agree with results from previous grid experiments (e.g., Catchpole et al., 2006; Valentinsson and Ulmestrand, 2008). The size dependent loss of *Nephrops* above MLS can largely be attributed to the grid. Neither Catchpole et al. (2006) nor Valentinsson and Ulmestrand (2008) documented any loss of legal sized *Nephrops* caused by the 35 mm grid. However, Catchpole et al. (2006) did not measure the *Nephrops*, which means

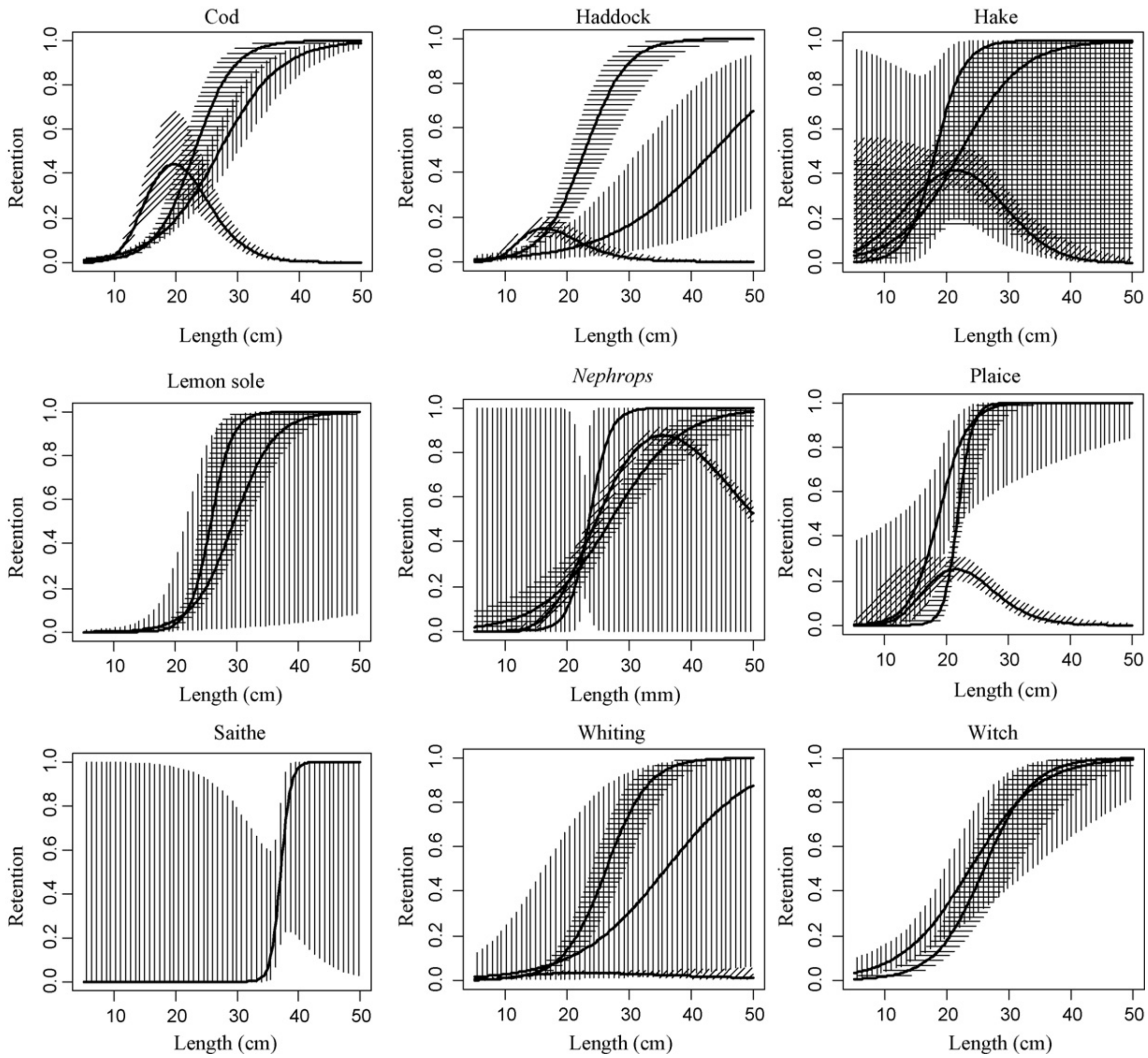

Fig. 5. Selection curves for all three gear types tested. For the grid codend, selection is based on the lower three-quarters (35 mm bar distance) of the grid only. Approximate 95% confidence bands are shown as hatched zones. Standard codend: horizontal hatching; SMP codend: vertical hatching; and grid codend: inclined hatching.

that change in the size composition of the catch might be masked (e.g., by higher catch rates).

Compared to no loss in previous experiments, the loss caused by the grid found in our study was high and may have been caused partly by different size compositions of the *Nephrops* in the investigated areas, by different methodology, and by differences in the gear design. In some previous experiments a guiding funnel has been used in combination with the grid and this is likely to increase catches of *Nephrops*. A guiding funnel may however alter the behaviour of roundfish and thus induce them to attempt to swim between the bars and into the codend instead of escaping through the escape hole. Due to the increased bar spacing that potentially allow larger fish to enter the codend, it was decided to avoid any obstructions in front of the grid in this experiment.

Escapement of cod and haddock below MLS was significantly reduced in the codend when the grid was used. An increase in catches of undersized cod and haddock was also reported by Catchpole et al. (2006) who tested a grid (35 mm bar distance) in combination with a 85 mm diamond mesh codend. They attributed the change in selective properties of the codend to the change in catch composition and catch quantities. In today's legislation, the grid is allowed only in combination with a 70 mm square mesh codend, which is expected to increase the release of small gadoids (e.g., Robertson and Stewart, 1988). However, experiments conducted in the Farn Deeps (England) showed a significant loss of legal sized (North Sea MLS) *Nephrops* from this codend (Catchpole et al., 2006). Valentinsson and Ulmestrand (2008) on the other hand, found no indication of loss of legal sized (Kattegat/Skagerrak MLS) *Nephrops* when testing the same gear. These opposite results may be a consequence of the difference in MLS, but an investigation of the estimated selection parameters for *Nephrops* in a 61.6 mm square mesh codend (Larsvik and Ulmestrand, 1992) indicate that a loss of *Nephrops* above 40 mm (Kattegat/Skagerrak MLS) is likely to occur. Extrapolated to a 70 mm (EU-wedge) square mesh codend by use of the *SF* value found by Larsvik and Ulmestrand (1992) and an assumption of a constant relation between the selection parameters, L_{50} and *SR* are estimated to be 43.9 mm and 14.7 mm, respectively. Using these parameters to predict loss in numbers of *Nephrops* from the size distribution found in this experiment, result in a loss of 44% of the legal sized (Skagerrak/Kattegat MLS) *Nephrops* from the square mesh codend. In combination with a grid, the loss through the codend meshes may be reduced as the catch quantity and composition change, but some loss is expected to occur.

4.4. Recommendation

A perfect match between gear regulations and MLS will not eliminate discard. In mixed species fisheries, discard is also a con-

Table A1
Approximate selection curves $\tilde{r}_{eff}(\cdot;\boldsymbol{\theta})$ and corresponding log-linear forms $\log(\tilde{r}_{eff}(\ell;\boldsymbol{\theta})) = [\beta_0] + [\beta_1]\cdot f_1(\ell) + [\beta_2]\cdot f_2(\ell)$ derived from a normal, a log-normal, and a gamma density.

Model	Selection curve	Log-linear form of the selection curve
Normal	$\omega \cdot \exp\left(-\frac{(\ell-\ell_0)^2}{2\sigma^2}\right)$	$\left[\log\omega - \frac{\ell_0^2}{2\sigma^2}\right] + \left[\frac{\ell_0}{\sigma^2}\right]\cdot\ell + \left[-\frac{1}{2\sigma^2}\right]\cdot\ell^2$
Log-normal	$\frac{\omega}{\ell}\cdot\exp\left(-\frac{(\log\ell-\ell_0)^2}{2\sigma^2} - \frac{\sigma^2}{2} + \ell_0\right)$	$\left[\log\omega - \frac{\ell_0^2}{2\sigma^2} - \frac{\sigma^2}{2} + \ell_0\right] + \left[\frac{\ell_0}{\sigma^2} - 1\right]\cdot\log\ell + \left[-\frac{1}{2\sigma^2}\right]\cdot\log^2\ell$
Gamma	$\frac{\omega\ell}{(\alpha-1)k}\cdot\exp\left(\alpha - 1 - \frac{\ell}{k}\right)$	$[\log\omega + (\alpha-1)(1-\log(\{\alpha-1\}k))] + [\alpha-1]\cdot\log\ell + \left[-\frac{1}{k}\right]\cdot\ell$

Table A2
Selection parameters of the three bell shaped selection curves.

Model	Modal length (ℓ_0)	Spread (σ)	Modal value (ω)
Normal	$-\frac{\beta_1}{2\beta_2}$	$\sqrt{-\frac{1}{2\beta_2}}$	$\exp\left(\beta_0 - \frac{\beta_1^2}{4\beta_2}\right)$
Log-normal	$\exp\left(-\frac{\beta_1}{2\beta_2}\right)$	$\sqrt{\left\{\exp\left(-\frac{1}{2\beta_2}\right) - 1\right\}\exp\left(-\frac{2\beta_1+3}{2\beta_2}\right)}$	$\exp\left(\beta_0 - \frac{\beta_1^2}{4\beta_2}\right)$
Gamma	$-\frac{\beta_1}{\beta_2}$	$\sqrt{\frac{\beta_1+1}{\beta_2^2}}$	$\exp\left(\beta_0 + \beta_1\left\{\log\left(-\frac{\beta_1}{\beta_2}\right) - 1\right\}\right)$

sequence of quota, of and catch composition regulations, and of market prizes. E.g. when quotas are limiting landings of one species, catches of this species is likely to be high-graded or discarded. However, optimizing the selectivity of the gear with regards to the MLS of the targeted species, will reduce the discard of juvenile fish.

This study documents a severe mismatch between regulations of minimum mesh size and MLS in the Kattegat–Skagerrak *Nephrops* fishery. Action is needed to reduce the resulting high discard rates. The SMP is well accepted by the industry because the loss of catch is limited, and the SMP codend is easy to handle at sea. However, we found that the overall effect of the SMP on the reduction of discard was significant ($p < 0.05$) only for haddock. Further investigations are needed to improve the ability of the SMP to sort out undersized gadoids if the gear is to be efficient in reducing discards. Such improvements could include an increase in SMP mesh size or a more aft position of the SMP.

The grid efficiently sorted out fish by-catch and fulfilled the aim of decoupling *Nephrops* and fish. However, the novel concept of increasing bar distance in part of the grid did not solve the problem of loss of legal sized *Nephrops*. As a management measure, a grid may be of interest in areas otherwise closed to the fishery. But means to reduce loss of the target species should be investigated, as should means to reduce discard of undersized fish without causing further loss of *Nephrops*. Furthermore, the fishermen expressed concerns about handling the grid which, in rough weather, brought about an extra element of hazard.

None of the gears investigated in this study reduced discards of undersized *Nephrops*. *Nephrops* stocks in Kattegat/Skagerrak currently show no signs of over fishing, according to ICES, but discard of any commercially important species constitutes suboptimal exploitation of the stock and should be avoided. Means to reduce discards of *Nephrops* should therefore be included in future studies.

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Appendix A

See Tables A1 and A2.

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Paper II

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A simulation-based attempt to quantify the morphological component of size selection of *Nephrops norvegicus* in trawl codends

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ABSTRACT

The selectivity for *Nephrops* (*Nephrops norvegicus*) in trawl codends generally is poor and the lack of steepness of the selection curve results in high discard rates and/or loss of legal-sized catch. This poor codend selectivity often is attributed to the irregular shape of *Nephrops*, which to some extent characterizes the problem as insoluble. In the present study, the FISHSELECT methodology was used to examine the selection process of the species in order to identify ways to improve selectivity. The use of three different modes of orientation for contact (contact modes) with the codend meshes explained most of the characteristics of the selection curves for *Nephrops* obtained experimentally. The contact mode with the smallest cross-section was optimal for mesh penetration and, when evaluated against experimental data, 87.5% of all *Nephrops* encountering the gear were estimated to meet the netting in this contact mode. The range of configurations of the meshes (e.g., opening angles in the diamond mesh netting) was determinative for the selectivity, and the selective process for *Nephrops* was found to take place along the entire length of the codend. Simulating selectivity in a diamond mesh codend in which the closed meshes in the forward part of the codend were replaced by more open meshes revealed that the selectivity for *Nephrops* can be efficiently improved.

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1. Introduction

The largest part of the Danish *Nephrops* (*Nephrops norvegicus*) quota is fished using trawls. In the Kattegat and Skagerrak, the minimum mesh size in the codend is 90 mm, and investigations have shown that up to 50% of the *Nephrops* caught are discarded because they are below the minimum landing size of 40 mm carapace length (CL) (Frandsen et al., 2009). Several studies have focused on the survival of the discarded *Nephrops*, and these have reported survival rates ranging from 12 to 85% (e.g., Evans et al., 1994; Castro et al., 2003; Harris and Ulmestrand, 2004). A positive effect on survival of increasing gear selectivity depend on the assumption that survival of *Nephrops* that escape the gear during fishing exceed the survival of discarded *Nephrops*. Data on this issue are, however, sparse but investigations of survival of other species indicate that this assumption is justified (Broadhurst et al., 2006).

Codend size selectivity for *Nephrops* is in general problematic. Compared to that of many fish species, the slope of the selection curve in the widely used diamond mesh codends is not very steep (Briggs, 1986), which results both in high discard rates and in losses of marketable catch. One reason for this problem is assumed to be the irregular shape of *Nephrops* (e.g., Briggs, 1986). Furthermore, the towing speed of the trawl largely exceeds the swimming speed of *Nephrops*, and their orientation when encountering the netting is therefore assumed to be random. Observations of *Nephrops* behaviour in the gear confirm this, as they have been seen to roll along the lower sheet of netting (Main and Sangster, 1985; Robertson and Ferro, 1991; Briggs, 1992).

An ideal fishing gear for *Nephrops* fishing would have a steep selection curve. This would provide the possibility to reduce discards without affecting the marketable catch simply by adjusting the mesh size. The aim of the present study was to obtain a better understanding of the size selection processes for *Nephrops* in trawl codends. Specifically, we addressed the following questions:

(i) Why is the selection curve for *Nephrops* much less steep than that for many fish species?
(ii) Can anything be done to increase the steepness of the selection curve for *Nephrops*?

We attempted to answer these questions using a morphological approach, and for this purpose we adopted and further developed the FISHSELECT methodology (Herrmann et al., 2009). This method identifies the morphological limitations of individuals that determine their ability to penetrate meshes of different sizes and shapes.

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The data obtained from this method subsequently were used in an integrated structural model to simulate the fishing process and predict the selective properties of new codend designs (Herrmann et al., 2009). In this study, the methodology was enhanced to incorporate a selection process that is composed of multiple elements, namely different contact modes.

Relationships between CL and parameter values that describe the cross-section shapes for different contact modes as required in FISHSELECT were established. Furthermore, relationships between CL and a number of other morphological measures were obtained in this study.

2. Methods

The selection curves of two different codends were estimated in the field, and the FISHSELECT method was subsequently used to explain the obtained selection curves. FISHSELECT is a framework of methods, tools, and software developed to determine whether an individual is able to penetrate a given mesh based on a comparison between the cross-section geometry of the individual and the mesh shape. Previously, the framework was used for fish that are assumed to orient themselves optimally for mesh penetration. Here, the methodology was modified to handle *Nephrops*, which presumably are oriented randomly when they meet the mesh. The selection curve of the codend is thus assumed to result from a series of different selection processes; each determined by the orientation of the *Nephrops*. A number of well-defined contact modes were identified, and their ability to permit passage through different mesh shapes was investigated.

To estimate the relative contributions to the resulting selectivity of the different contact modes, we ran a high number of stochastic simulations. Between each simulation, the contributions of the individual contact modes were varied randomly by the values of the assigned weighting factors. The output of the simulations was an equally high number of proposed selection curves that were ranked according to their similarity to the experimentally obtained selection curve. The combination of weighting factors that was found to be most accurate in reproducing the experimental selection curves was assumed to reflect the properties of the selection process in the specific trawl codend. Because we expected less variations in mesh shapes when the square mesh codend was used, the procedure was conducted for this case first to assess realistic values for the weighting factors of the different contact modes. Subsequently, these values were used in an attempt to explain the selection curve obtained for the diamond mesh codend.

A thorough pilot study was executed in the laboratory to identify a suitable set of contact modes that, when combined, might explain the selection process found in the field. A final experiment was performed on a large number of individuals that were investigated with regard to their morphology and their ability to penetrate different meshes using the contact modes defined in the pilot study. Morphological data obtained in the final experiment allowed us to create a virtual population to be used for more flexible simulations of codend selectivity.

2.1. Reference data from a field experiment

In 2006, the selectivity of a 68.1 mm (standard deviation (SD) = 1.1 mm) square mesh codend (S68) and a 90.1 mm (SD = 1.4 mm) diamond mesh codend (D90) was estimated in a covered codend experiment (100 meshes of both codends were measured with an ICES gauge with the spring load set at 4 kg). Stretched lengths of the codends were 6 m and the mean catch weights were 126 kg (SD = 75.9 kg) and 184 kg (SD = 104.1 kg) for the S68 and the D90, respectively. Covers were made of 36 mm square mesh netting in the area surrounding the codend and 36 mm diamond mesh netting in the remaining part. The sea trials were conducted on board the commercial twin-rig trawler FN234 "Canopus" in September 2006 (Fig. 1), and details about gear design and experimental setup will be published elsewhere. We needed information about average selectivity, so data from the 18 hauls were pooled. Retention rates were subsequently estimated as the fraction of the total catch (cover + codend) retained in the test codend for each length group (Fig. 2). The estimated selection curves for these experimental data were required to evaluate the FISHSELECT simulations and we therefore fitted different types of curves to the data. Based on investigations of residual plots it was concluded that the standard logistic curve did not provide a good description of the entire range of data for the S68 codend. Estimates of L_{50} (length at 50% retention) and *SR* (L_{75}–L_{25}) would therefore not be representative of the information contained in the data set. The residual plot of a LogitS3 curve indicated that this curve represented the entire data range of the S68 codend well.

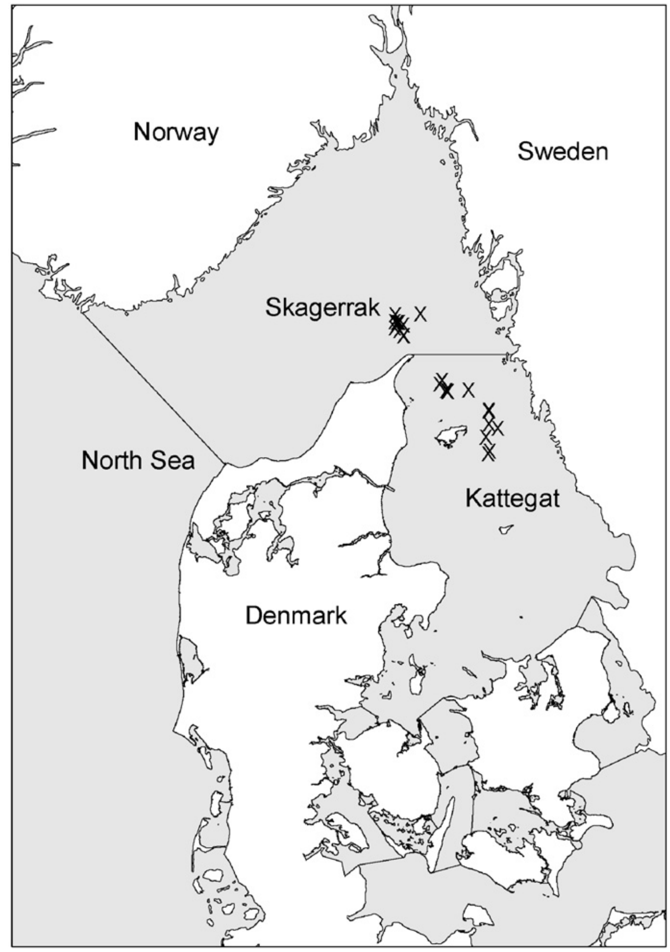


Fig. 1. The location of the field experiment. Hauls are shown as crosses.

The LogitS3 curve is the sum of three logistic functions in which the weights of the contributions add up to 1.0. Over the entire selective range, the LogitS3 curve provided a better representation of the experimental data. The resulting values from L_{05} to L_{95} (Fig. 2) were used to rank the simulated data with regard to their similarity with the experimental data. The selective range of the D90 codend was only partly covered in the experimental data. The standard Logit curve (Wileman et al., 1996) was fitted to these data and to avoid extrapolation, the evaluation of simulations against experimental data was restricted to comparisons of L_{75}–L_{95}.

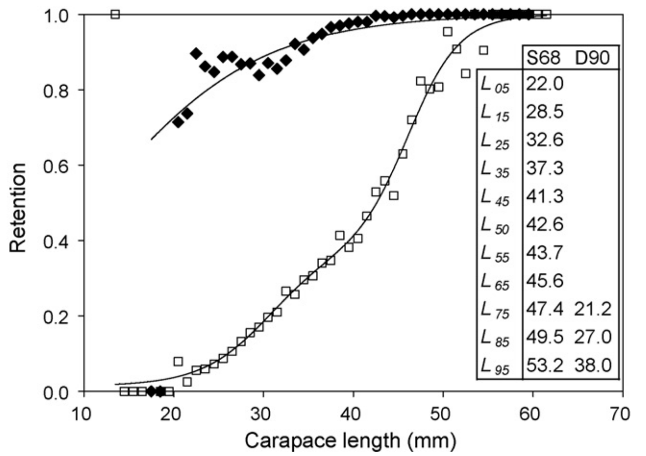
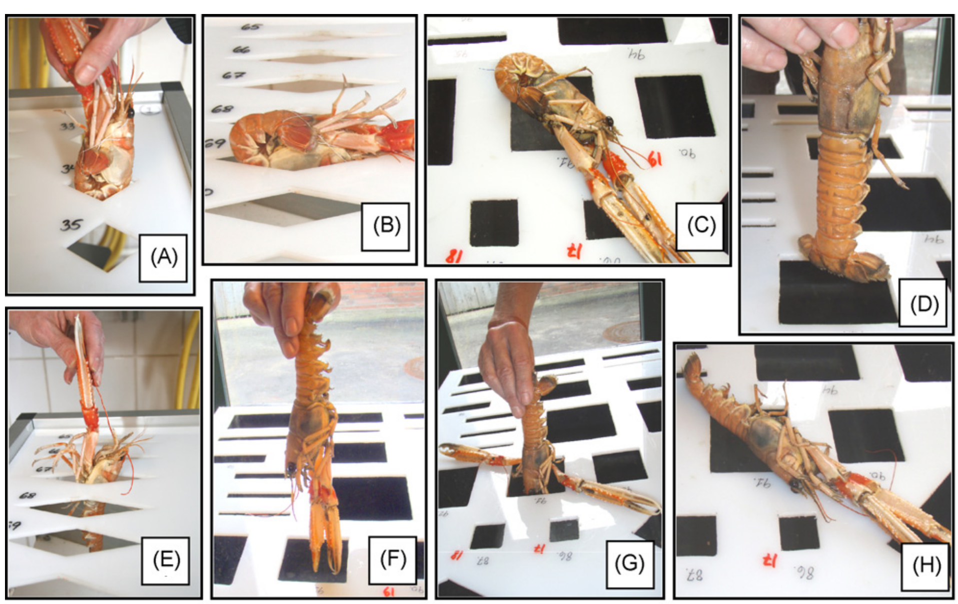


Fig. 2. Experimentally obtained selection data for the D90 (black diamonds) and S68 (white squares) codends. The estimated selection curves are shown as solid lines and the estimated retention data for the two codends are given in the inserted table.

Because some selection may have occurred in the cover, we simulated the selectivity of *Nephrops* in the cover and investigated whether it could have influenced our results (see Section 3.3).

2.2. Pilot study

The FISHSELECT methodology was used in a pilot study to identify potential contact modes and evaluate their relative importance in the selection process. The aim of the pilot study was to identify a limited number of contact modes, which, in combination, could be deemed capable of reproducing size selection of *Nephrops* in a trawl codend. Twenty *Nephrops* with CLs ranging from 18 to 61 mm were tested for their ability to penetrate meshes in a standard FISHSELECT fall-through setup (Herrmann et al., 2009). Forty-three mesh templates were chosen to represent different degrees of mesh openings of a 70 mm square mesh and a 90 mm diamond mesh. Use of approximately the same mesh sizes as those used in the field experiment (Section 2.1) allowed us to evaluate the test results against the experimental data. Eight contact modes representing different angles of contact between the individual and the netting were identified and investigated (Fig. 3), including the contact mode with the smallest cross-section which was optimal for mesh penetration (Fig. 3E). For each of the eight contact modes, the pilot study yielded 20 × 43 = 860 fall-through results, comprising a total of 6880 results. The only morphological measure taken in the pilot study was CL and, in contrast to the traditional FISHSELECT methodology, the results from the fall-through experiments were used directly to simulate selection in a 70 mm square mesh codend. Fall-through results from all mesh templates representing the square meshes were combined by randomly assigning different levels of contribution to the used contact modes. Because 70 mm is very close to the mesh size of the S68 codend used in the field experiment, we assumed that the simulated selection curves based on the fall-through results could be compared with the field results. The outcome of this comparison allowed us to evaluate which of the eight investigated contact modes could be potential candidates to simulate size selection for *Nephrops*. Contact modes that resulted in simulated retention data that obviously conflicted



A Tail is flexed and the animal penetrates the mesh abdomen first. Vertical orientation is optimal at all times which may result in turning the animal during mesh penetration.
B Tail is flexed and the animal penetrates the mesh carapace first. Vertical orientation is optimal.
C Tail is flexed and the animal penetrates the mesh sideways. Vertical orientation is optimal.
D Tail fan is spread out and the animal penetrates the mesh tail first. Vertical orientation is optimal at all times which may result in turning the animal.
E The animal penetrates the mesh tail first. Vertical orientation is optimal at all times which may result in turning the animal.
F The animal penetrates the mesh claws first. Vertical orientation is optimal at all times which may result in turning the animal.
G First pair of legs (long claws) is spread out and the animal penetrates the mesh head first. Vertical orientation is optimal at all times.
H The animal penetrates the mesh sideways. Vertical orientation is optimal.

Fig. 3. Contact modes tested in the pilot study. In the final study only modes A, B, and E were used.

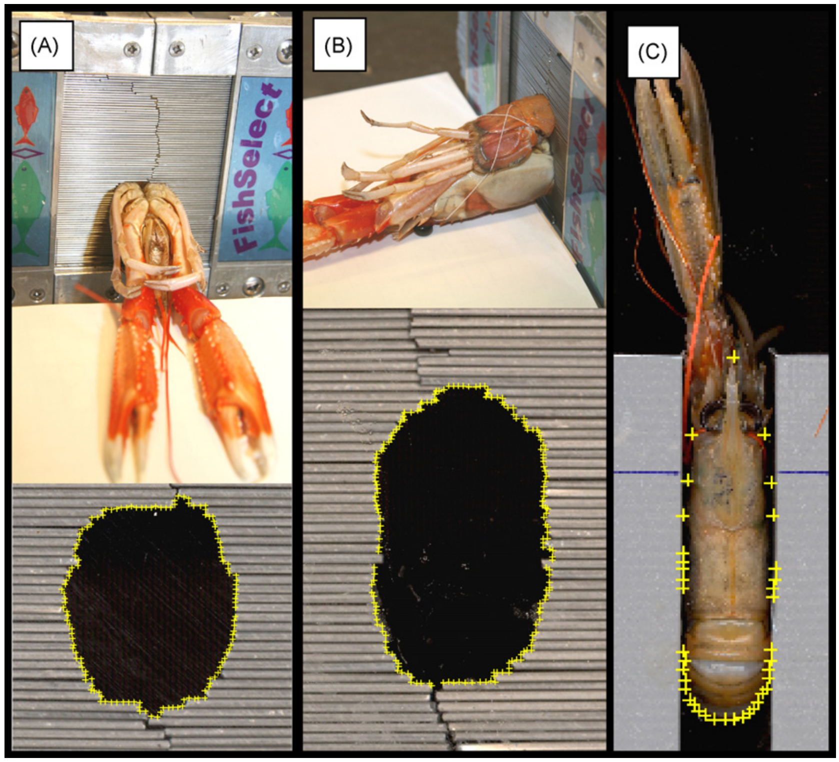


Fig. 4. CS1 (A), CS2 (B), and CS3 (C) being measured in the MorphoMeter (CS1 and CS2) and being scanned (CS3). Scanned images of the MorphoMeter (lower panels of A and B) also show the automatic contour detections (crosses) performed by FISHSELECT. Contour detection was performed manually for CS3 (crosses).

with the experimentally determined selective range for the S68 codend were eliminated from further analyses. Furthermore, for some modes we obtained identical or nearly identical fall-through results for all 20 individuals for all 43 meshes. We assumed that just one of these contact modes was needed to represent them all; we chose the simplest mode to test experimentally and eliminated the others from further analysis. Based on the procedures described above, three contact modes (A, B, and E) (Fig. 3A, B, and E) were found which, in combination, could be used to simulate size selection for *Nephrops* in trawl codends; these three modes were selected for the final experiment.

As mentioned above, the use of raw fall-through results for simulating codend selectivity differs from the traditional FISHSELECT methodology in which fall-through results are related to cross-section shapes and simulations are subsequently based on the relationships between CL and the parameters of these cross-sections. The benefit of applying the more simple procedure for the pilot study is that it eliminated the need to measure and model a large number of different and complicated cross-sections, some of which were bound to be eliminated later in the process. The drawback of our approach is that it cannot be used to make predictions outside the few meshes and *Nephrops* involved directly in the study. To circumvent these restrictions, the standard FISHSELECT methodology was applied in the final experiment, and the knowledge obtained in the pilot study allowed us to reduce the number of contact modes from eight to three.

2.3. Final experiment

In November 2007, 70 *Nephrops* with CLs ranging from 22.5 to 68.5 mm (31% females) were collected at sea and frozen individually. The defrosted *Nephrops* were used in the experiment. To validate this method the entire range of lab experiments were run twice on two *Nephrops*; in the first run the *Nephrops* were anaesthetized and in the second run they were defrosted. The results showed that freezing did not affect their cross-section shapes or their ability to penetrate meshes. Newly moulded (soft-shelled) *Nephrops* were not used in the experiment.

2.3.1. Measurement of cross-section shapes and other morphological measures

Three cross-sections were measured, corresponding to the three contact modes selected in the pilot study. The position of the first cross-section (CS1) was at the base of the 2nd pair of walking legs (Fig. 4A) and it represented the largest cross-section of contact mode E. The second and the third cross-sections were based on animals with a flexed abdomen; to obtain a constant flex during measurements, a string was tied from the base of the tail fan around the carapace to the rostrum. The second cross-section (CS2) was at the 1st abdominal segment of the flexed abdomen (Fig. 4B) and represented contact mode A. The third cross-section (CS3) was laid out horizontally along the longitude axis of the animal with flexed abdomen and it represented contact mode B; it sectioned the animal from the tip of the rostrum to the posterior part of the flexed abdomen (Fig. 4C). A down-scaled version of the MorphoMeter described in Herrmann et al. (2009) was developed and used to measure CS1 and CS2. The diameter of the measuring sticks in this version of the MorphoMeter was reduced from 2.5 to 1.2 mm, which enabled a more precise acquisition of the small cross-sections of the *Nephrops*. Due to its position, CS3 could not be measured using the MorphoMeter; instead, images of the *Nephrops* lying on a flatbed scanner were used (Fig. 4C). For subsequent measures of total length, carapace width, carapace height, and width of the 2nd abdominal segment, three different images of each individual were captured using the flatbed scanner (Fig. 5).

2.3.2. Estimation of cross-section shape

The cross-section contours of CS1 and CS2 were extracted from the scanning images of the MorphoMeter using image analysis functions in the FISHSELECT software (Fig. 4A and 4B). The contour

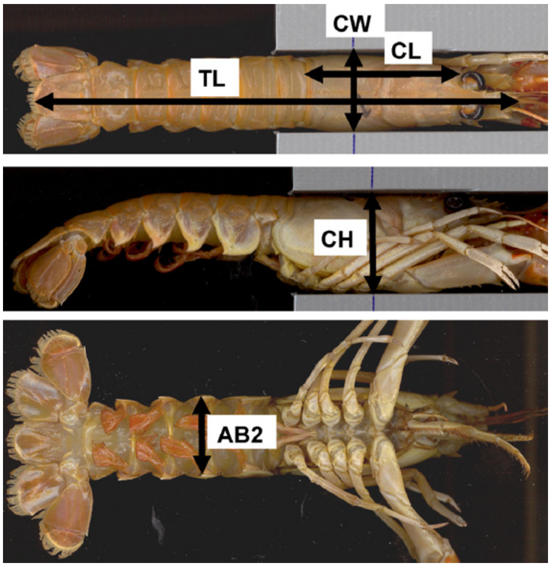


Fig. 5. Position of morphological features measured from the scanning images (CW, TL, CH, and AB2) and by use of a caliper (CL). CW: carapace width, TL: total length, CH: carapace height, AB2: width of 2nd abdominal section, and CL: carapace length.

of CS3 was manually digitized from the scanning image (Fig. 4C). To simplify the descriptions of the three cross-sections, different geometric shapes were fitted to each contour using the least-square fitting method included in the software. It uses a non-negative merit function: The smaller the merit value, the better the description of the measured cross-section (Herrmann et al., 2009). The cross-sections of *Nephrops* were not well described by the basic geometric shapes incorporated in the original FISHSELECT framework, thus new descriptions were developed and tested; of them, two new shapes were applicable to *Nephrops*. We named the shapes "ship" and "flex-ellipse," and both can be described by three parameters (see Appendix A for definitions of the shapes). In addition, the merit of a standard ellipse was estimated. The parameters describing the chosen geometric shapes were subsequently related to CL using regression functions (Herrmann et al., 2009). These relationships and their variations were used when creating virtual populations for the simulation of selectivity (Herrmann et al., 2009).

2.3.3. Fall-through experiments

The fall-through trials in the final experiment were conducted using 160 different mesh templates cut out in 5 mm thick polyamide plates (Table 1). The mesh templates included four different types (diamond, square, hexagonal, and rectangular) of stretched (stiff) meshes with sizes ranging from 60 to 270 mm. The three contact modes selected from the pilot study were tested (Fig. 3A, B, and E). The fall-through experiment was thus run three times for each *Nephrops* specimen ($N = 70$). The experiment was carried out as outlined in Herrmann et al. (2009). A total of 33,600 results were generated containing information on success or failure of the *Nephrops* to penetrate a given mesh template using each of the three contact modes.

2.3.4. Simulating fall-through results

The geometric cross-sections obtained for each individual in Section 2.3.2 were used to simulate success or failure of a given individual to penetrate a given mesh in the fall-through experiment as described by Herrmann et al. (2009).

As in the fall-through experiment, the simulations were performed three times for each individual, corresponding to contact modes E, A, and B, respectively. The simulated results were compared to the experimental results and the degree of agreement (DA) was calculated as described in Herrmann et al. (2009). DA ranges from 0 to 100% and indicates 0–100% agreement between simulation and experiment. Disagreements between experimental and simulated results were ranked using a scaling factor that indicates how much the cross-section contour should be up-scaled (scaling factor > 100) or down-scaled (scaling factor < 100) for the simulation to yield the same result as the experiment (Herrmann et al., 2009).

Table 1
Mesh configurations tested in the final fall-through experiment. For the rectangular meshes, bar a is the short bar and bar b is the long bar. The definition of opening angle (oa) in hexagonal meshes follows Herrmann et al. (2009).

Mesh type	Mesh size (mm) (stretched mesh)										
	60	70	80	90	100	110	120	130	140	160	180	200
Diamond (oa)												
15		X	X	X			X			X	X	X
20		X	X	X	X	X	X	X	X	X		
25			X	X			X			X		
30		X	X	X			X			X		
35		X		X			X			X		
40		X		X			X			X		
45		X		X			X			X		
50		X		X			X			X		
55		X	X	X	X	X	X	X	X	X	X	X
60		X		X			X			X		
65		X		X			X			X		
70		X		X			X			X		
75		X		X			X			X		
80		X		X			X			X		
85		X	X	X	X	X	X	X	X	X	X	X
90[a]	X	X	X	X	X		X		X	X	X	X
Hexagonal (oa)												
40	X	X					X					X
60	X	X					X					X
70							X					
80	X	X					X					
90	X	X	X		X		X		X	X		X
105	X	X	X		X		X		X	X		X
130	X	X	X		X		X		X	X		X
145	X	X	X		X		X		X	X		X

Mesh type	Mesh size (mm) (bar b)										
	60	70	80	90	100	110	120	130	140	160	180	200
Rectangular (bar a)												
10				X			X					X
15				X			X					X
20				X			X					X
30				X			X					X
35												X
40												X
45												X
50				X			X					X
60												X
70				X			X					X

[a] Corresponds to square meshes.

2.3.5. Simulating codend selectivity

Estimation of the selectivity of the entire codend includes assessment of the relative occurrence of the three contact modes as well as assessment of the distribution of different mesh configurations (i.e., opening angles (oa) for diamond meshes and squareness factor ($SFA = 100 \times a/b$, where a and b are bar lengths (Herrmann et al., 2009)) for square meshes).

2.3.5.1. *Mesh configurations in the codends.* Theoretically, square meshes under unidirectional tension (determined by the direction of towing) may either assume the shape of hexagons (i.e., the tensionless bars can be deformed) or rectangles (i.e., the tensionless bars are either shortened or bend in a direction perpendicular to the sheet of netting, meaning that the resulting mesh shape cannot be altered under an attempt to penetrate the mesh). Due to their passive behaviour and low weight, we assume that *Nephrops* are unable to deform the mesh bars and that the resulting meshes in a square mesh codend therefore are rectangular. This assumption was backed up by an initial simulation study where square meshes were regarded as hexagons. This resulted in a dissimilarity between simulated and experimental results in the upper part of the selection curve. This point of the selection curve is an important fix point when simulating retention as it defines the maximum size of a *Nephrops* that can pass through the mesh.

Simulations for a series of rectangular meshes were performed based on the 68 mm square mesh, all with one bar (bar b) measuring 34 mm and the other (bar a) ranging from 10 to 34 mm, resulting in SFA values ranging from 29 to 100%. The 90 mm diamond mesh was also used as a base for simulations, assuming a series of diamond meshes having oas ranging from 0.1° to 90°.

2.3.5.2. Relationship between contact mode and mesh configuration. Knowledge about the relationship between the contact mode of the *Nephrops* and the mode's ability to allow mesh penetration for different mesh configurations is essential for understanding the role of each contact mode in determining the details of the selection curve. Reduced versions of the design guide described in Herrmann et al. (2009) were used to obtain this knowledge. The design guides are based on simulations using a virtual population of *Nephrops*, and for each mesh configuration they illustrate the L_{50} for all three contact modes. The virtual population was created using the morphological relationships obtained previously (see Section 2.3.2) and contains a total of 2000 individuals randomly selected between 5 and 80 mm CL.

2.3.5.3. Combining contact modes and mesh configurations. For any one of the mesh configurations, each contact mode results in a specific selection curve. The selection curve for the codend results from contributions from all of the specific selection curves representing the different contact modes and mesh configurations present in the codend. If one contact mode is more likely than others, the selection curves of this mode will be given a higher weighting factor and thus have more influence on the codend selection curve than the other modes.

To determine the relative contribution of the different modes and meshes, 2,000,000 simulations were run on the virtual population of *Nephrops* described in Section 2.3.5.2. In each simulation, values for the weighting factors were either assigned random values (weighting factor = 0–100%) or fixed values (e.g., if the distribution of mesh configurations was known). Within a run, the weighting factor of a specific contact mode was set to be the same for all mesh configurations. We thus assumed that the resulting value of the weighting factor w_{ij} obtained by combining any contact mode i with any mesh configuration j could be approximated by:

$$w_{ij} = w_{\mathrm{mode}_i} \times w_{mesh_j}$$

where w_{mode} is the weighting factor for the contact mode and w_{mesh} is the weighting factor for the mesh configuration. The weighting factors were always assigned values that complied with the normalization criteria:

$$\sum_i w_{\mathrm{mode}_i} = 1.0, \qquad \sum_j w_{mesh_j} = 1.0$$

To evaluate the codend retention data obtained when simulating selection for *Nephrops* encountering a codend with a specific combination of meshes and with a specific occurrence of contact modes, we used the selectivity estimates of L_{05}–L_{95} (Fig. 2) obtained experimentally. A merit value was used to rank simulated selection curves with regard to their similarity to the experimentally obtained selection curve:

$$Merit = \sum_i \left(\frac{L_{sim_i} - L_{\mathrm{exp}_i}}{L_{\mathrm{exp}_i}} \right)^2,$$

$$i \in \{05, 15, 25, 35, 45, 50, 55, 65, 75, 85, 95\}$$

where L_{sim_i} and L_{exp_i} are the i% retention lengths obtained by simulation and experiments, respectively. L_{exp} was estimated as described in Section 2.1, and L_{sim} was estimated automatically using the non-parametric methods implemented in the FISHSELECT software.

In the case of the D90 codend, our experimental results only covered retention values from L_{75} to L_{95}, and we therefore restricted evaluation of the simulated results to this range ($i \in \{75, 85, 95\}$).

2.3.5.4. Prediction of codend selectivity. Identification of the relative importance of the different contact modes also allows us to predict the selectivity of codends that have not yet been tested experimentally. This requires knowledge about the mesh configurations in the codend. To explore the effect of controlling this parameter on size selection of the codend for *Nephrops*, a set of simulations was run for diamond mesh codends; each simulation included a different range of oas.

Table 2
Fit statistics given as mean and standard deviation (SD) of the merit value of the geometric shapes fitted to the measured cross-sections. (see illustrations in Fig. 6).

	CS1		CS2		CS3	
	Mean	SD	Mean	SD	Mean	SD
Ellipse	0.97	0.90	0.90	0.62	5.20	2.55
Flex-ellipse	0.72	0.60	0.53	0.36	4.57	2.57
Ship	0.76	0.61	0.79	0.60	2.67	1.27

3. Results

3.1. Morphological measures and cross-section shapes

Cross-sections were fitted to three different geometric shapes. The simplest shape tested was an ellipse, but for all cross-sections more complex shapes requiring more parameters were needed to describe the contours satisfactorily (Fig. 6, Table 2). The flex-ellipse was the best shape for describing both CS1 and CS2, and the ship was the best shape for describing CS3. The parameters of the geometric shapes are related to CL (Fig. 7), and the R^2 value (percentage of variance explained) for the regressions ranged from 0.96 to 0.99 for parameters c_1 and c_2. These parameters define height and width of the geometric shape and were expected to be strongly correlated with CL (see Appendix A). The lowest R^2 values were attributed to the c_3 parameter, which defines deviation from an ellipse. R^2 values for the regressions of c_3 versus CL for CS1 and CS2 were particularly low (0.48 and 0.49). However, because both the absolute value and the standard deviation of parameter a (see formula in Fig. 7) in these regressions are low compared to that of c_1 and c_2 for the same cross-sections, the effect of the relatively low R^2 on the length-based regressions of virtual populations is expected to be small. Therefore, we considered the length relationships of the cross-section shapes to be well defined, which justifies the use of these parameters to create a virtual population. Because the observed variation in parameters was incorporated into the creation of the virtual population, the variation among individuals was also included in the simulations, and this made the output more realistic.

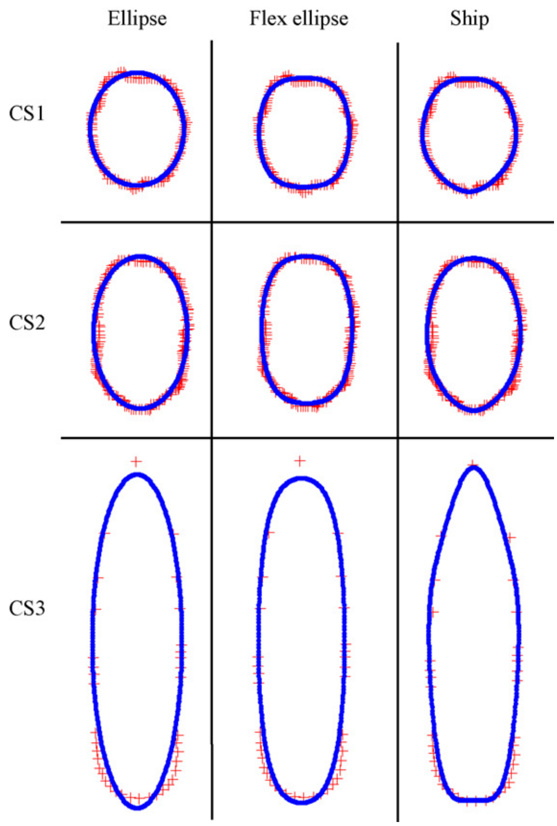


Fig. 6. Cross-section contours of the *Nephrops* (crosses) and the geometric shapes fitted to the contours (blue line). Mean fit statistics are given in Table 3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Relationships between CL and a number of other morphological measures (Fig. 5) were evaluated by regression to power functions (Table 3). Comparison of the 95% confidence bands of the regressions only revealed a significant difference ($p < 0.05$) between genders for the width of the 2nd abdominal segment, which is broader for females. Data for males and females were therefore pooled for all other relationships. R^2 values were high (>0.978), thus the measures could be predicted from the CL with a high degree of certainty.

3.2. Simulations of the fall-through results

The fall-through results for the three modes considered in the final experiment were simulated. Because *Nephrops* has a hard exoskeleton, we assumed the cross-section contours to be uncompressed during mesh penetration. Under this assumption, the DAs for modes A, B, and E were 97.4%, 95.9%, and 98.6%, respectively.

Table 3
Morphologic relationships between carapace length (CL) measured using an electronic caliper and a number of measures ($y = a \times CL^b$). Total length, carapace width, carapace height, and width of the 2nd abdominal segment were estimated from scanning images. (see illustrations in Fig. 5).

y	*a*	*b*	R^2
Weight	0.0003	3.214	0.990
Total length (TL)	3.8000	0.960	0.992
Carapace width (CW)	0.3556	1.104	0.986
Carapace height (CH)	0.4869	1.079	0.992
Width of 2nd abdominal segment (AB2)			
Females	0.4851	1.008	0.984
Males	0.4469	1.071	0.978

The measurement error resulting from the use of the FISHSELECT MorphoMeter, the scanning technique, and image analysis in combination has been estimated to be at most 5% (Herrmann et al., 2009). When we disregarded disagreements between simulated and experimental fall-through results below 5%, the DAs for modes A, B, and E were 99.1%, 98.2%, and 99.7%, respectively. We used the distribution of the scaling factors to check for skewness, which would indicate a tendency to either overestimate or underestimate the ability of individuals in a specific mode to penetrate the meshes (Fig. 8). Skewness towards scaling factor values >100 were found for all modes, but the tendency was most pronounced for modes A and B. This indicates that the simulation model slightly overestimated the ability of penetration and that a higher DA could be obtained by expanding the cross-section contours somewhat. Such an expansion could be justified by the fact that legs are neglected when measuring the cross-sections, although they may influence fall-through results. This is, however, speculative and we therefore chose to accept the relatively low number of disagreements obtained for the model using unexpanded cross-sections in the simulations.

The high agreement between the data from the fall-through experiment and the simulations indicates that the measured cross-sections and their parametric descriptions can be used to explain the mesh penetration of the tested modes. This in turn justified our use of the cross-sections in the further analysis of codend selectivity.

3.3. Simulating codend selectivity

For each mesh configuration (size and oa for diamonds and size and SFA for rectangles), a selection curve was estimated based on the simulated retention data for each contact mode. These simplified selection curves were thus freed from all other sources of influence on their *SR* values except that caused by variation in morphology among individuals. Because variation in the selection process among individuals is directly reflected in the shape (i.e., the lack of steepness) of the selection curve, we used *SR* to estimate the morphological contribution to variation in the selection process. The *SR* values of the simplified selection curves were small (0.17–3.51 mm), and we therefore assumed that the morphological contribution to the relatively large *SR* values of the selection curves obtained in the field is small compared to that of other potential contributors, such as variation in mesh configurations and variation caused by a mix of contact modes. Due to the approximate "knife-edge" nature of the selection curve for a single mesh configuration and contact mode, the values of L_{50} versus oa or SFA shown in the design guides in Fig. 9 are sufficient to illustrate similarities and differences in selectivity between the three contact modes. For the S68 codend (Fig. 9A), modes A and E gave similar values of L_{50} when meshes were nearly closed, but they differed more as the meshes opened up. Mode E was the optimal contact mode for penetrating the meshes as it represents the smallest cross-section of the *Nephrops*. The retention of *Nephrops* in this mode was therefore important in determining the upper end of the selection curve. For all mesh openings, contact mode B had the lowest values of L_{50} and the retention in this mode therefore was important in determining the lower end of the selection curve.

Investigations of images of square mesh codends in flume tanks and under fishing condition (e.g., Robertson et al., 1986) have indicated that a realistic range of SFA in a square mesh codend is 47–94%. We therefore restricted the square mesh configurations to this range when simulating codend selectivity for the S68 codend.

Identification of the relative importance of the three contact modes was based on the experimental data from the S68 codend (see Section 2.1). First, simulated retention in all S68 mesh configurations (nine meshes with equally spaced values of SFA in the range

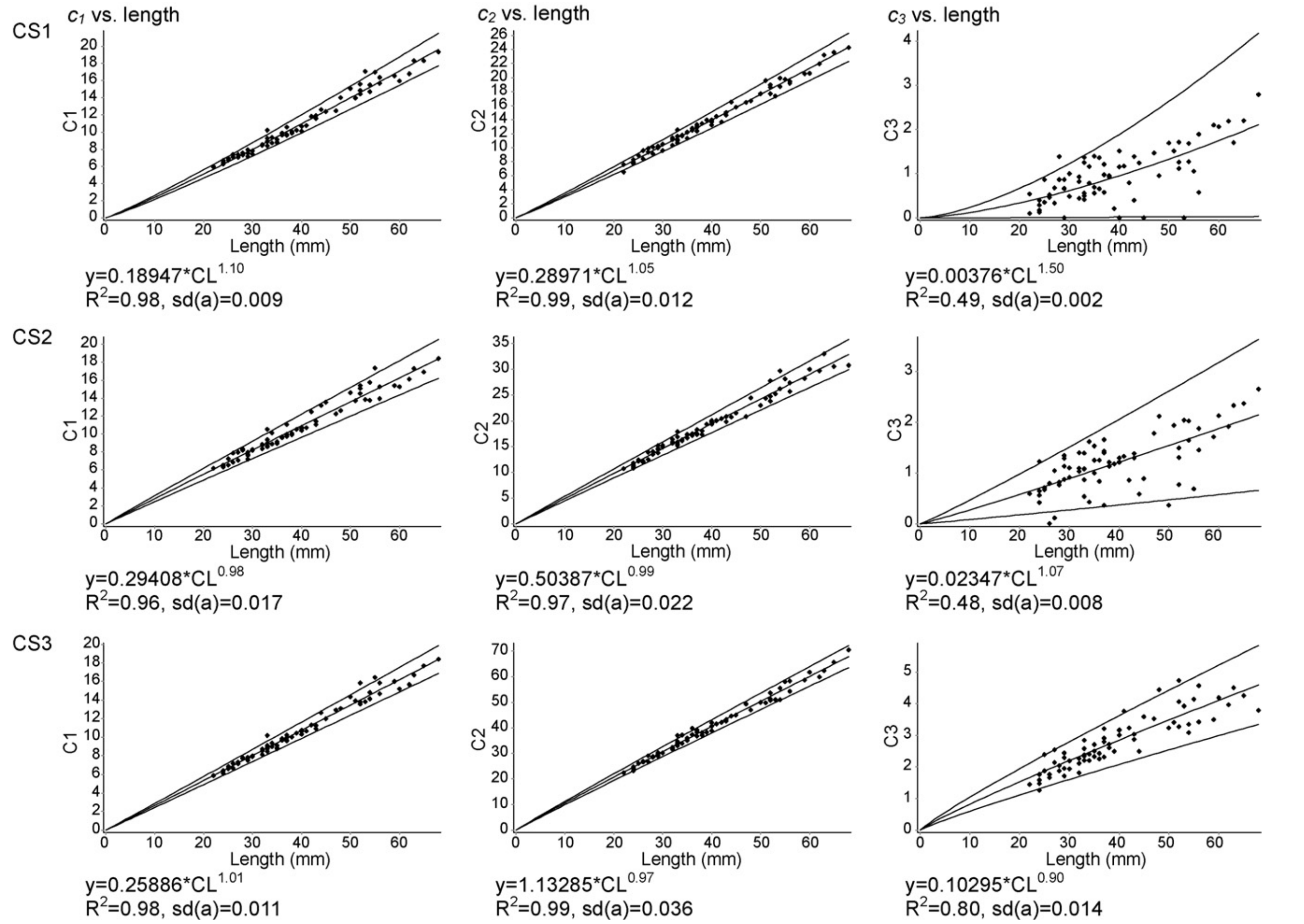


Fig. 7. Length-based regression lines ($y = a \times \mathrm{CL}^b$) for the three parameters that describe the geometric shapes of the flex-ellipse (CS1 and CS2) and the ship (CS3). 95% confidence limits for the simulated variation between individuals in these regressions are shown. Fit statistics are given as R^2 and standard deviation on a (SD(a)).

47–94%) was combined for each mode separately to determine if one mode alone could explain the selection curve found for experimental data (Fig. 10A). A set of simulations in which the weighting factors of the mesh configurations were randomly chosen also was investigated (data not shown), but irrespective of the weighting factors, the use of one single mode could not satisfactorily explain the entire range of retention in the experimental data.

The relative occurrence of mesh configurations in a square mesh codend is unknown, but a conservative base line is to assume that all of the configurations indicated above (i.e., SFA = 47–94%) occur with the same frequency. All mesh configurations were therefore assigned the same weighting factor, and 2,000,000 simulations were run with constant weighting of the meshes and random weighting of the contact modes. The resulting codend retention data were ranked as described in Section 2.3.5.3 and the mean values of the weighting factors of the 100 best fits were assumed to reflect the relative representation of the three contact modes in the selection process. Mean values of the relative occurrence of the contact modes in the S68 codend were: 5.8%, 6.7%, and 87.5% for modes A, B, and E, respectively. The simulated retention data corresponding to the highest rank is shown in Fig. 10B.

The experimental results from the diamond mesh codend (D90) were used to validate the assumption that the chance that a given *Nephrops* will encounter a mesh with a specific contact mode is independent of the mesh shape in the codend. The weighting factors for the three modes found to best reproduce the experimental results in the S68 codend were used when simulating selection curves for the D90 codend. 2,000,000 simulations were run with constant weighting of modes and random assignment of weighting factors to eight oas equally spaced in the range 0°–35°. As for the S68 codend, the resulting codend retention data were evaluated against the experimentally obtained retention data, but in the case of the D90 codend, only retention data for L_{75}–L_{95} were available (Fig. 2). The mean weighting factors of the mesh openings in the 100 best fits were assumed to reflect their representation in the selection process (Table 4). The simulated retention data with the highest rank are shown in Fig. 10C.

The distribution of mesh openings in diamond mesh codends also can be theoretically estimated from information about the codend design using methods described in O'Neill (1997) or Priour (2001). Based on information given in Herrmann et al. (2006) obtained using FEMNET (Priour, 2001), it is possible to obtain a rough estimate of the range of oas and their expected occurrence in a 100 mm diamond mesh codend made of 4 mm double twine netting. We assumed that the distribution of oas in that codend is comparable to that found in the D90 codend (5 mm double twine)

Table 4
Weighting factors for opening angles (oas) estimated by FISHSELECT for the D90 codend. Mean value and standard deviation (SD) for the best ranked 100 simulations are given.

	Mean oa							
	0	5	10	15	20	25	30	35
Mean	23.6	23.5	23.0	13.7	6.0	4.4	3.9	2.1
SD	10.0	8.7	8.0	3.6	2.9	2.7	2.0	1.4

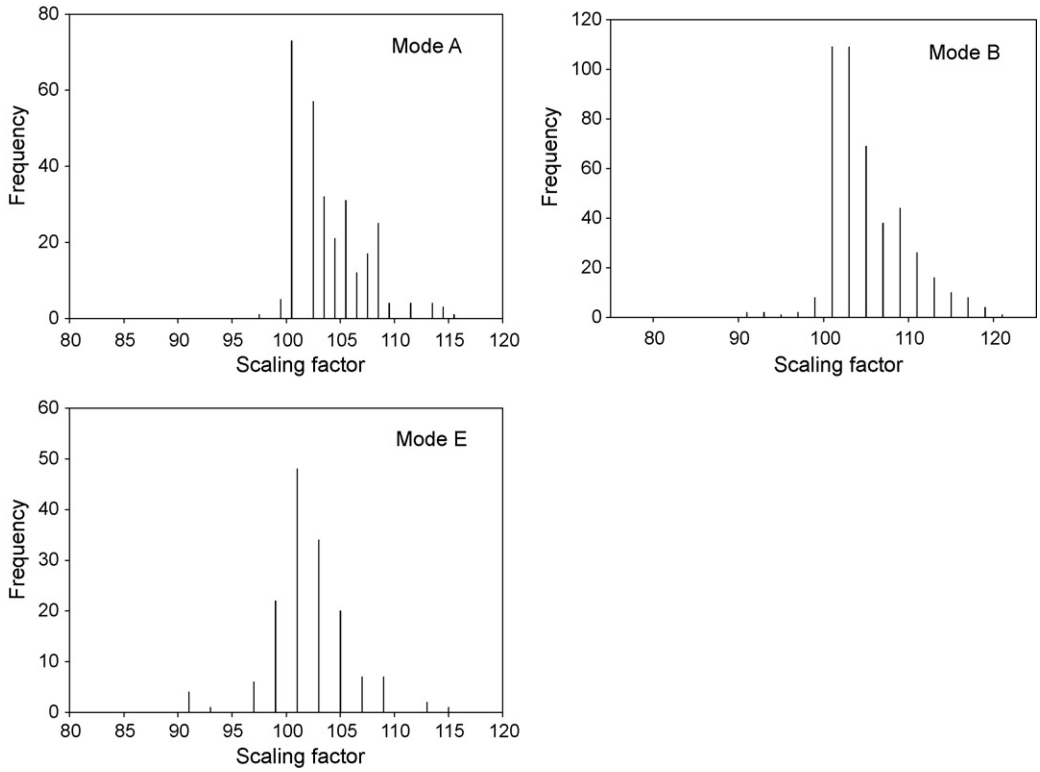


Fig. 8. Distribution of the scaling factor values for disagreeing results when comparing experimental and simulated fall-through results.

used in the present experiment. At catch weights around 90 kg, which corresponds to the assumed catch weight half way through the haul in this study, the distribution of oas is expected to range from 0° to 35°. Seventy percent of the meshes would have oas between 11.5° and 17.5°, whereas 20% of the oas would be between 17.5° and 27.5° and the remaining 10% of the meshes would have oas between 27.5° and 35°. Based on the simulated weighting factors given in Table 4, we calculated a similar division of the simulated oa ranges. Our simulated results indicate that approximately 70% of the diamond meshes in the codend range in opening from 0° to 12.5° and the remaining 30% have mesh openings between 12.5° and 35°.

We also used FISHSELECT to determine if cover selection could have affected the retention data obtained experimentally and, if this was the case, to what extent this could be expected to influence our simulated results. The potential selectivity of the cover was simulated and, in order to define the size of the largest *Nephrops* able to escape through the cover meshes, we looked at the optimal orientation (mode E) and the optimal mesh configuration (SFA = 100%). L_{50} for this combination of contact mode and mesh configuration was 29.4 mm, indicating that there is a risk of cover selection of individuals below this size. For the S68 codend, a CL of 29.4 mm approximately corresponds to L_{20}. To test if cover selection would affect the weighting factors of the contact modes, we eliminated the lower part of the experimentally obtained selection curve and thus evaluated 100,000 simulations only against experimental data in the range L_{25}–L_{95}. The best fit was given a weighting factor of mode E of 87.9%, which is similar to that obtained when exploiting the entire selective range for evaluation. Thus, we believe that the cover effect would not affect the distribution of contact modes in the case of the S68 codend (which were later used in the case of the D90 codend).

3.4. Prediction of codend selectivity

The weighting factors for the contact modes defined for the S68 codend were used to investigate the possibility of controlling the selectivity for *Nephrops* in diamond mesh codends by reducing

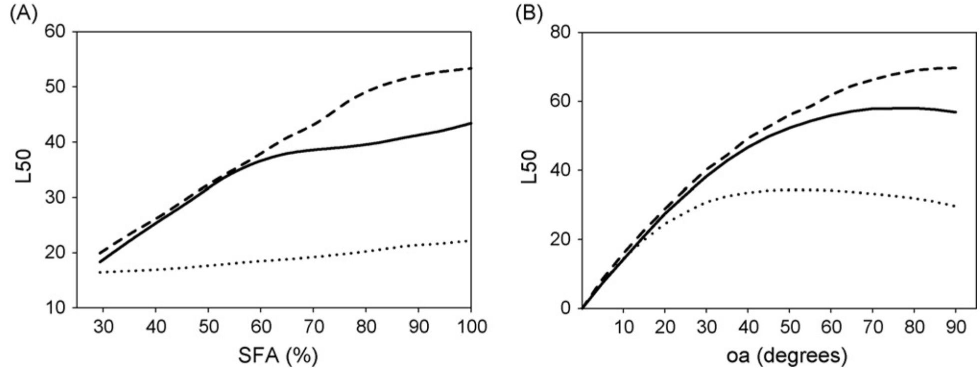


Fig. 9. Design guides for the three contact modes in the S68 (A) and the D90 (B) codends. Mode A: solid line, mode B: dotted line, mode E: hatched line.

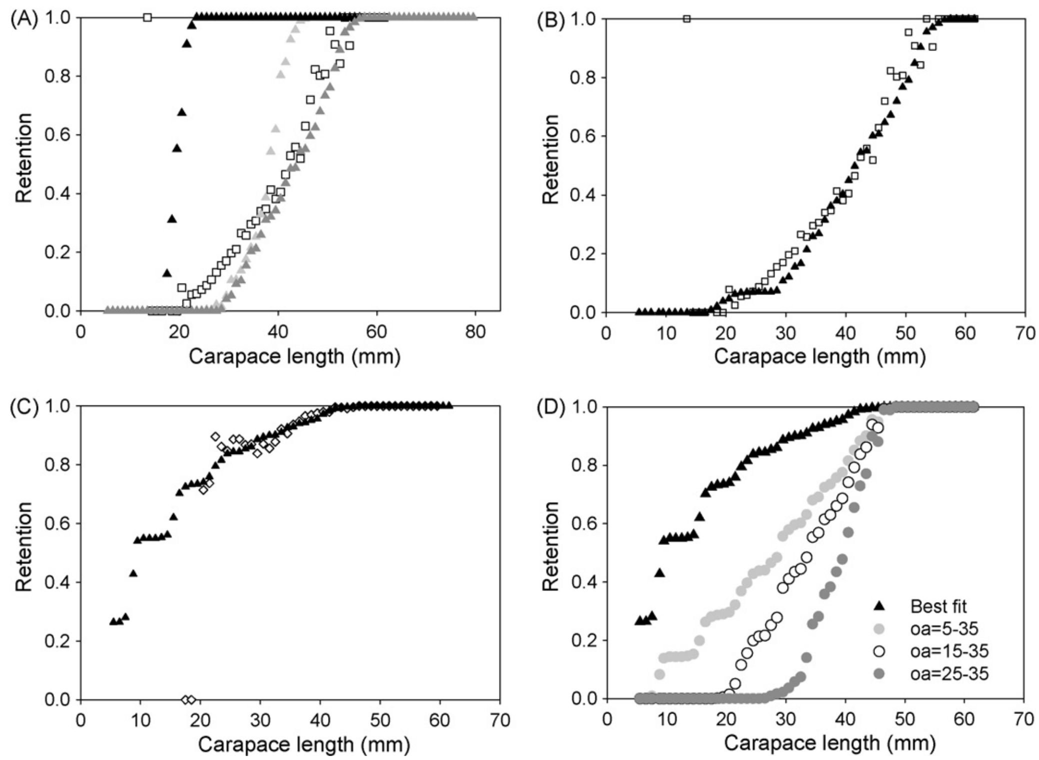


Fig. 10. Simulated and experimental retention data. (A) Data for the S68 codend were simulated for each of the three contact modes separately. Mode A: pale gray triangles, mode B: black triangles, mode E: dark gray triangles, experimental: white squares. (B) Highest ranking simulated (black triangles) and experimental (white squares) retention data for the S68 codend. Simulations included all three contact modes and were based on equal weighting factors for all mesh configurations. (C) Highest ranking simulated (black triangles) and experimental (white diamonds) retention data for the D90 codend. Simulations included all three contact modes with their weighting factors fixed at the values obtained from the analysis of the S68 codend. (D) Effect on retention data of reducing the range of opening angles (oas) in the diamond mesh codend. Data shown are simulated retention data for the D90 codend and include all three contact modes with weighting factors fixed at values obtained from analysis of the S68 codend. In the data for the best fit, weighting factors were adjusted to best fit the experimental data. In simulations of codends with a reduced range of oas, weighting factors of the oas were equal.

the range of oas. Techniques such as shortened lastridge ropes can reduce the tension in the meshes, thereby causing the oas of meshes far from the catch build-up to increase. With this in mind, we investigated three scenarios in which different fractions of meshes with small oas were removed from the simulations. We assumed all mesh configurations within the chosen range to be equally likely, and they therefore were assigned the same weighting factor. The three scenarios were defined by having oas ranging from 5 to 35, 15 to 35, and 25 to 35 (Fig. 10D). The effect on the selection curve of eliminating meshes with small oas and increasing the occurrence of meshes with large oas was an increase in the steepness of the selection curve.

4. Discussion

The present study illustrates that the FISHSELECT methodology can be used to explain experimentally obtained selectivity data on *Nephrops* for a square mesh codend and a diamond mesh codend. The selectivity of codends for this species has previously been regarded as complex due to the animals' irregular body shape and their ability to aggregate using their claws. However, our results show that a relatively simple model can, to a large extent, explain the selectivity by combining data about morphology for a few contact modes and mesh configurations in the codend. Our results also illustrate that the steepness of the selection curve can be increased by reducing the variation in mesh configurations in the codend.

The morphology of *Nephrops* related to the three contact modes could be well described by parametric shapes and all cross-section parameters could be estimated from CL with high precision. This fact justifies implementation of the structurally based FISHSELECT methodology, as it uses nothing but morphology and mesh configuration to predict selectivity of nettings. The high degree of agreement between simulations and fall-through results also indicates that the morphological features that determine the ability of *Nephrops* to penetrate meshes with the chosen contact modes were well captured in the chosen cross-sections. Furthermore, it justifies the assumption that the exoskeleton of *Nephrops* remains un-deformed during mesh penetration.

The creation of a virtual population with CLs ranging from 5 to 80 mm was based on extrapolations for both the small and the large individuals. However, the high precision in estimating the parameters defining the cross-sections within the range of measured *Nephrops* (22.5–68.5 mm) justifies this. Furthermore, the downward extrapolation was constrained by the structurally fixed point of 0,0, indicating that all morphological measurements would be zero at CL = 0, which makes the extrapolation more permissible (Fryer and Shepherd, 1996). For most selectivity studies on *Nephrops*, the lack of small individuals has severely affected the precision when estimating the codend selection, as retention data are restricted (e.g., to L_{75}–L_{100}, as was the case for the D90 codend data presented in this study).

When simulating codend selectivity, a high number of parameters that can be adjusted to achieve a specific output may increase the risk of accepting an erroneous model. Therefore, in the present study we fixed all parameters for which we had reasonable knowledge about their value. Thus, codend selectivity for the S68 codend was achieved by adjusting the weighting factors of only three parameters (the contact modes), whereas the values for the weighting factors for the nine different mesh configurations were fixed. The output equalled the experimentally achieved retention data down to approximately L_{30}. Beneath this value, the simulated retention data fluctuated around the experimental data, and we assume that this discontinuity is due to the simplification of using just three contact modes. However, to a large extent the model reflected selectivity in the entire selective range, which justifies our assumptions about mesh configurations in a square mesh codend and about the ability of the chosen contact modes to explain the selective process of *Nephrops*. It also justifies the use of mesh templates to imitate selection in codend netting. The optimal mode (mode E) was assigned the highest weighting factor (87.5%), which indicates that the majority of *Nephrops*, at some point during their travel through the codend, encounter a mesh in an orientation that is optimal for escape. This scenario, however, likely requires that the codend is long enough to ensure a high number of randomly oriented contacts between *Nephrops* and netting. Visual observations of *Nephrops* rolling on the lower sheet of netting (e.g., Main and Sangster, 1985) and thereby having numerous attempts to escape may explain the observations in the present study. However, the optimal contact mode is not sufficient to explain the selective process, and within the 100 best simulations the two other modes were consistently given weighting factors ranging from 4.9 to 7.2%. The design guide for the S68 codend illustrates that the sub-optimal modes are needed to explain cases in which small individuals are retained by relatively large and open meshes. More detailed knowledge about the variation in the distribution of the three contact modes could be obtained by testing the methodology against other sets of experimental data that cover the entire selective range.

While the optimal contact mode is indisputable, as it represents the smallest cross-section of *Nephrops* and explains the upper part of the selection range seen in experimental data, the other contact modes are likely to represent a range of sub-optimal attempts of escape through the meshes (rather than being exact modes). The three modes can be viewed as the minimum range of different quantifiable orientations that are needed to explain the selectivity found in the field. Including more contact modes in the model might increase the accuracy of the model, particularly in reproducing the lower part of the S68 codend retention data, but it would also increase the risk of accepting an erroneous model.

The relative weighting of the three modes was assumed to be independent of the mesh shapes in the codend, and it was therefore re-used when simulating selectivity in the D90 codend. The range of retention that could be evaluated in the D90 codend was limited by the size range of *Nephrops* caught in the field experiment, but within this range the simulations easily fit the experimental data by adjusting weightings of the eight mesh configurations used. In addition, the simulated distribution of the oas in the codend exhibited a very similar pattern to what was theoretically expected for the upper range of oas; however, the simulations tended to overestimate the contribution of the smaller oas. Discrepancies between expected and simulated distribution of mesh configurations were thus most pronounced for the small oas, and this may be explained by the knots, which in diamond mesh codends may functionally close the mesh due to knot-to-knot contact for small oas. This effect was not included in our simulations; instead we assumed that the meshes were knotless. Simulated diamond meshes with very small oas are thus better at representing the selective potential of knotted diamond meshes with larger oas that are functionally closed. Because the effect of the knots increases with increasing twine diameter, it is fair to assume that the fraction of functionally closed meshes was underestimated in the expected values of the relatively heavy twine (double 5 mm) used in this experiment. For the more open meshes just in front of the catch build-up, we assume this effect to be negligible and not to affect escapement of fish that primarily escape through this rearmost part of the codend (Beverton, 1963). The position of the decisive mesh contact of *Nephrops* is, however, assumed to be randomly distributed over the full length of the codend. Another effect related to the twine thickness of the codend netting is that the codend tested in the field experiment was made of 5 mm double twine, whereas the expected oas according to Herrmann et al. (2006) were based on 4 mm double twine netting. This difference in twine thickness is expected to lead to a bias corresponding to an overestimation of the oa values (Herrmann and O'Neill, 2006). We conclude that the re-use of weighting factors for the contact modes obtained for the S68 codend led to reasonable results for the D90 codend. Our results also support the assumption that selectivity for *Nephrops* is determined by mesh configurations in the entire length of the codend.

We found that the effect of cover selection did not bias the results obtained in the case of the S68 codend. However, due to the poor selectivity of the D90 codend, individuals within the selective range of the D90 codend may have escaped through the cover. This would have led to an overestimation of retention within this range, thereby making the selectivity of the codend seem to be poorer than it actually was. A CL of 29.4 mm approximately corresponds to L_{85} in the D90 codend. To what extent cover selection affected the estimated selectivity of the D90 codend is unknown. But the reasonable agreement between the distribution of oas in the codend found by simulation and the expected oas makes it less likely that cover selection has affected the estimated selectivity of the D90 codend.

We initially asked the following two questions: Why is the selection curve for *Nephrops* much less steep than that for many fish species, and can anything be done to increase the steepness of the selection curve for *Nephrops*? According to our findings, the low slope value of the selection curve often found for *Nephrops* can be explained by the different contact modes and by assuming that the contact between the individual and the netting takes place throughout the entire length of the codend. In particular, diamond meshes have a wide range of mesh configurations that depend on distance from the catch build-up, and this contributes to the high variation in the chance that an individual will successfully escape through the meshes. An increase in the steepness of the selection curve is desirable, as it would make reduction in discard of individuals below the minimum landing size possible without increasing the loss of legal-sized catch. The predictions of selectivity for *Nephrops* in diamond mesh codends, where meshes with small oas are avoided, clearly indicate that this approach efficiently alters the selection curve by increasing the steepness. In diamond mesh codends, a reduction in the range of oas can be obtained by using shortened lastridge ropes, which reduce tension in the bars.

Using a structural model such as that in FISHSELECT allows prediction of selectivity of codends that have not yet been tested experimentally. In this way, better starting points for the expensive and time-consuming sea trials can be provided. This will reduce the number of sea trials and the process of gear development will therefore be faster. The methodology is not limited to specific mesh shapes and it can be used to predict selectivity of codends composed of different nettings (e.g., codends with escape panels or codends with grids).

Acknowledgements

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Appendix A.

To describe the cross-section shapes of *Nephrops* for the three different contact modes, FISHSELECT requires a representation in polar coordinates (θ, r), where θ is the angle (0–2π) and r is the corresponding radius (Appendix in Herrmann et al., 2009). A description involving only few parameters is preferred. A flexible method is to use a parametric description in Cartesian coordinates on the form (Bers and Karal, 1976):

$$\begin{matrix} x = f(t) \\ y = g(t) \end{matrix} \quad t \in [0, 2\pi]$$

The polar representation of the points on the cross-section surface is then calculated by:

$$r = \sqrt{x^2 + y^2}$$
$$\theta = \tan^{-1}(y, x)$$

in which our representation returns the angle in the correct quadrant.

To represent the cross-section of *Nephrops* for the three modes, three parametric representations were found to be relevant (called "ellipse," "ship," and "flex-ellipse" in this paper). The ellipse is a standard shape and needs no further description, but the other representations require three parameters (c_1, c_2, and c_3), all of which are considered as functions of CL:

- Ship:

$$f(t) = c_1 \times \sin(t)$$
$$g(t) = -c_2 \times \cos(t) + c_3 \times \cos(4t)$$

- Flex-ellipse:

$$f(t) = c_1 \times \sin(t)$$
$$g(t) = -c_2 \times \cos(t) + c_3 \times \cos(3t)$$

For both geometric shapes, c_1 and c_2 define the height and width of the figure and c_3 defines the actual deviation from the elliptic shape. If c_3 equals zero, both the ship and the flex-ellipse will take the shape of an ellipse.

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Paper III

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Selectivity and escapement behaviour of five commercial fishery species in standard square- and diamond-mesh codends

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Frandsen, R. P., Madsen, N., and Krag, L. A. 2010. Selectivity and escapement behaviour of five commercial fishery species in standard square- and diamond-mesh codends. – ICES Journal of Marine Science, 67: 000–000.

The Danish fishery for *Nephrops* (*Nephrops norvegicus*) is often conducted in a mixed-species setting, characterized by high rates of discards of several target species, including *Nephrops* and cod (*Gadus morhua*). Experiments were conducted to investigate and compare the selective properties of a standard 70 mm square-mesh codend (standard SMC) and a standard 90 mm diamond-mesh codend (standard DMC). Selectivity estimates for five commercial species are provided for both codends. The standard SMC yielded higher estimates of length at 50% retention/mesh size (hereafter SF) for *Nephrops* and roundfish than did the standard DMC, but no effect of codend type on SF was found for plaice (*Pleuronectes platessa*). Moreover, a novel codend cover design allowed assessment of the preferred direction of escapement in the codend. Whiting (*Merlangius merlangus*) and *Nephrops* showed pronounced, but opposite, vertical preference in the direction of escapement, with whiting escaping upwards and *Nephrops* downwards. A significant ($p < 0.05$) difference in the direction of escapement between the two codends was found for haddock (*Melanogrammus aeglefinus*) and whiting. Owing to the relatively small catches, the outcome is probably most applicable to *Nephrops*-directed fisheries under similar conditions, and caution should be taken not to extrapolate the results to other fisheries.

Keywords: cover, escapement behaviour, *Gadus morhua*, Kattegat, mixed-species fishery, *Nephrops norvegicus*, *Pleuronectes platessa*, selectivity, Skagerrak, square-mesh codend, trawl.

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Introduction

Discarding of commercial species takes place at high rates in Danish mixed-species fisheries in the Kattegat and Skagerrak (Krag *et al.*, 2008). Among other species, *Nephrops* (*Nephrops norvegicus*), cod (*Gadus morhua*), and plaice (*Pleuronectes platessa*) are targeted. Discarding of cod gives cause for particular concern, because the International Council for the Exploration of the Seas (ICES) states that the stock is at a historically low level in the Kattegat and overfished in the Skagerrak (ICES, 2009). In recent experiments with commercial trawls, >50% by number of *Nephrops* caught were below the minimum landing size (MLS; 40 mm carapace length, CL; Krag *et al.*, 2008; Frandsen *et al.*, 2009). Investigations have shown that survival of discarded *Nephrops* ranges from 12 to 85% (Evans *et al.*, 1994; Castro *et al.*, 2003; Harris and Ulmestrand, 2004), while survival of the *Nephrops* that escape from the trawl during the fishing process is ~82% (Wileman *et al.*, 1999). Hence, the overall survival of undersized *Nephrops* could be improved significantly by making the fishing gear more size-selective.

Theoretically and experimentally, both mesh size and mesh shape affects the L_{50} (L_x is the length at which x% is retained) and the SR (selection range = $L_{75} - L_{25}$) of *Nephrops* significantly (ICES, 2007; Frandsen *et al.*, 2010). Compared with diamond-mesh codends, square-mesh codends with the same nominal mesh size are more size-selective, i.e. have a higher L_{50} and a lower SR (ICES, 2007; Frandsen *et al.*, 2010). Square-mesh codends also have good selective properties for roundfish such as cod (Halliday *et al.*, 1999), haddock (Robertson and Stewart, 1988; Halliday *et al.*, 1999), and whiting (Robertson and Stewart, 1988). For some species of flatfish, however, square-mesh codends yield lower values of L_{50} than the equivalent diamond-mesh codends (Walsh *et al.*, 1992; He, 2007). Therefore, the selective properties of square- and diamond-mesh codends differ for different morphological groups, such as for flatfish, roundfish, and *Nephrops*. The optimum mesh shape is theoretically related to the cross-sectional shape of the species (Herrmann *et al.*, 2009).

With knowledge of species-specific behaviour and the different selective properties, selectivity can be optimized by combining different netting materials in the same codend. Many earlier studies on species-specific behaviour focused on species separation at the mouth of the trawl (Main and Sangster, 1982). Once the fish have entered a trawl, they usually stay clear of the netting panels unless the straight path is blocked (Glass *et al.*, 1993; Glass and Wardle, 1995), so they travel towards the codend, where most escape attempts are made just in front of the catch build-up (O'Neill *et al.*, 2003; Jones *et al.*, 2008). Previous investigations of species-specific behaviour in the aft end of a trawl and in the codend have shown that *Nephrops* tend to remain low in the net (Briggs, 1992; Krag *et al.*, 2009a). Plaice also seem to stay low in the aft end of the trawl, but cod have a more uniform vertical distribution (Krag *et al.*, 2009a), and haddock and whiting stay high (Krag *et al.*, 2009a). Cod, haddock, and whiting have been reported to escape through square-mesh windows in the extension and upper panel of the codend (cod:

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Madsen *et al.*, 2010; haddock: Frandsen *et al.*, 2009; whiting: Briggs, 1992). We here document the vertical direction of escapement through the codend for five different species, so providing additional information on the selection process.

A 90 mm diamond-mesh codend with a 120 mm square-mesh window is included in the legislation for the Kattegat and the Skagerrak, and is commonly used. For most commercial species, however, the SR of this codend is high (e.g. cod 10.93 cm, haddock 18.56 cm; Frandsen *et al.*, 2009), so the risk of discarding and the loss of legal-sized fish is high. In addition, a 70 mm square-mesh codend is allowed, but only in combination with a rigid sorting grid (35 mm bar spacing). Selectivity experiments with square-mesh codends have been conducted in other *Nephrops* fisheries, using relatively small meshes (40–55 mm; Stergiou *et al.*, 1997; Bahamon *et al.*, 2006; Sala and Lucchetti, 2010), but only one experiment testing a square-mesh codend (60 mm) in the Skagerrak and Kattegat has been reported (Larsvik and Ulmestrand, 1992). The existing selectivity estimates for *Nephrops* in a 70 mm square-mesh codend are therefore based on extrapolations and assumptions.

To assess the selective properties of each type of netting, the codends we tested had no additional selective devices. Two codends, a commercial 70 mm (3 mm single twine) square-mesh codend (standard SMC) and a commercially used 90 mm (5 mm double twine) diamond-mesh codend (standard DMC), were investigated in terms of their selectivity for *Nephrops*, cod, haddock, plaice, and whiting. Also, the species-specific differences in the direction of escapement through the codend meshes were investigated with the aim of obtaining knowledge of the potential for species separation in the codend. Further, our experimental setup allowed between-trial variations in the estimated selection parameters to be assessed, because two trials using different vessels, trawls, and towing time were conducted.

Experimental methods

The selectivity of the codends was estimated using the covered codend method (Wileman *et al.*, 1996). Two codends were tested: a standard DMC with a nominal mesh size of 90 mm and a standard SMC with a nominal mesh size of 70 mm. Further information on the netting material is given in Figure 1. The standard DMC had 92 meshes around and the standard SMC had 90 bars around. On the basis of estimates of mesh openings in the standard DMC ranging from 0° to 35° and lengths of the tensionless bars in the standard SMC ranging from 47 to 94% of the stretched bar length (Frandsen *et al.*, 2010), the circumference of the two codends is estimated to be about the same. The netting material of both was the same as the netting used in commercial fisheries in the area.

Nephrops fishing is generally conducted on soft sediments, where the action of the trawl gear tends to cause resuspension of sediment. Hence, visibility is poor and divergence between visual observations and actual catch may arise under these conditions (Krag *et al.*, 2009b). Alternatives to visual observations for quantifying the reaction of fish to different netting panels are therefore needed. For this purpose, we developed a codend cover that was divided horizontally, providing an upper and a lower compartment (Figure 2). The horizontal partitioning panel in the cover constrained escapees to either the upper or the lower compartment, depending on the panel of the codend through which they escaped. The design, therefore, allowed estimation of the fractions of each species that escaped upwards or downwards through the codend. This novel cover design was developed and tested in full scale in the Hirtshals flume tank before the sea trials. Covers were made of polyethylene netting with a measured mesh size of 36.4 mm. A combination of kites, weights, and floats, as prescribed by Madsen *et al.* (2001), was used to maintain the geometry of the covers during fishing (Figure 2). The drag of this type of cover is expected to be relatively low (Madsen *et al.*, 2001). In both codends, the horizontal partitioning panel in the cover was attached to the seam of the codend, and the netting of the panel was orientated to form diamond-meshes. This design should minimize the influence of the cover on the mesh openings of the codend and leave the partitioning panel slack enough to allow movements of the codend. Inspection of the standard DMC with cover in the flume tank demonstrated that these requirements were met. Furthermore, the codend was clearly capable of assuming the bulbous shape characteristic for a diamond-mesh codend at catches as small as 150 kg. The bulbous shape causes the rows of meshes just in front of the catch build-up to be more open. To be able to conclude that fish and *Nephrops* that ended up in either the upper or the lower cover compartment had escaped through the corresponding panel of the codend, it is essential that no exchange between the two compartments is possible. The horizontal partitioning panel was made of the same small-mesh netting as the covers, and from the codline, the cover was divided into two separate compartments (upper and lower; Figure 2). As fish escape mainly through the open meshes just in front of the catch build-up, the distance they travel before they end up in the separate compartments is short. A potential exchange between the covers of the smallest fish is therefore restricted almost totally.

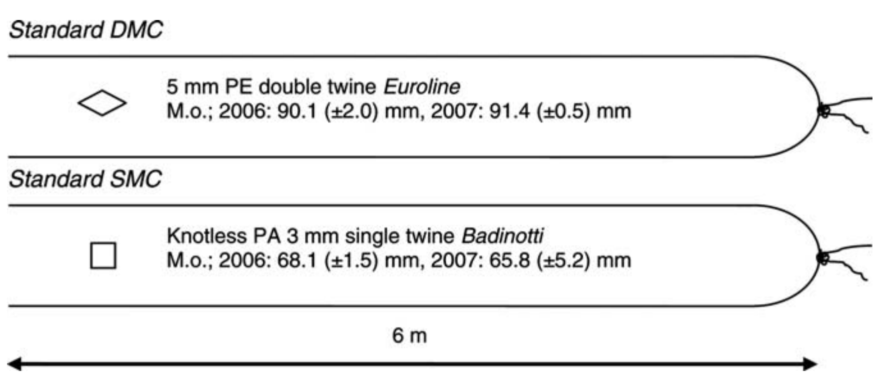

Figure 1. Experimental codends. M.o., mean mesh sizes measured by the ICES 4 kg wedge (95% confidence limits are in parenthesis); PE, polyethylene; PA, polyamide. Before and after the trials, 50 codend meshes were measured in a dry and a wet condition, respectively.

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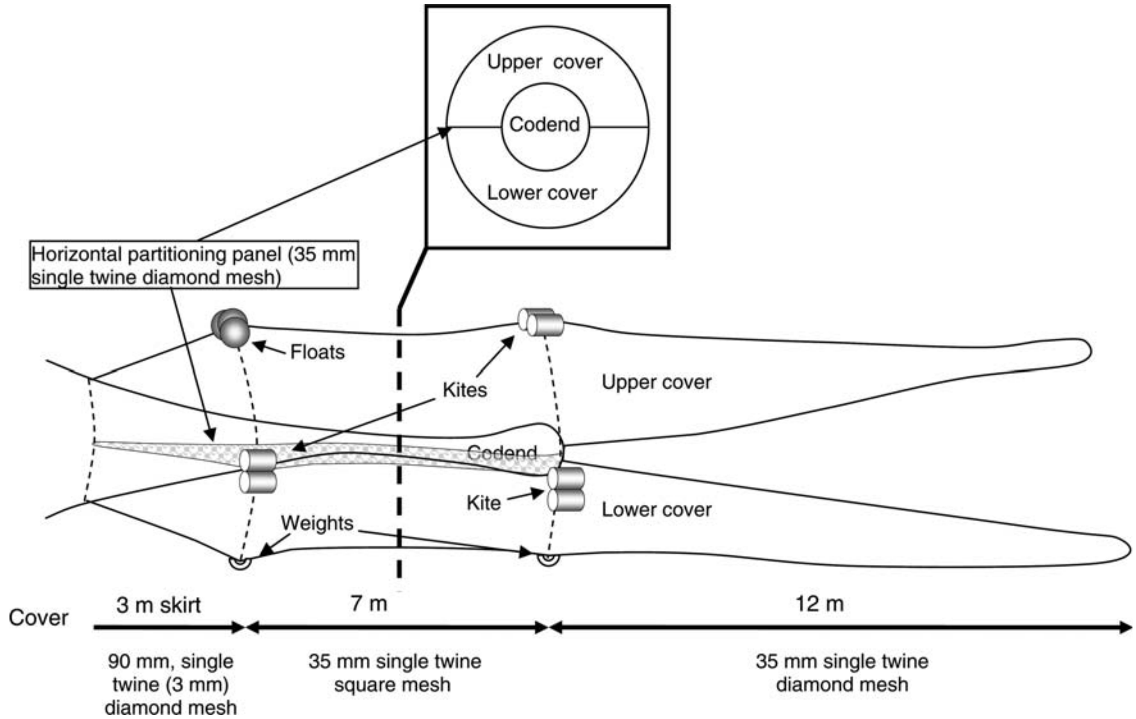

Figure 2. Cover design in cross section (upper drawing), and as seen from the side (lower drawing). The point at which the cross section is taken is indicated on the side view by a broken line.

Sea trials

Two cruises were conducted on-board commercial vessels in the Kattegat and the Skagerrak in 2006 and 2007 (Figure 3). In September 2006, the 294 kW stern trawler FN234 "Canopus" was used. It was rigged for twin-trawling with two identical trawls, which were combined fish and *Nephrops* trawls with a nominal mesh size of 80 mm and a circumference of 480 meshes. Design of the vessel limited the size of the cover catch that could be processed, so in 2007 a new vessel that allowed larger catches to be processed, and hence longer hauls, was chartered. In August 2007, the 386 kW stern trawler RS30 "Mette Amalie" was used. Like the "Canopus", it was rigged for twin-trawling with combined fish and *Nephrops* trawls with a nominal mesh size of 100 mm and circumference of 460 meshes. Choice of fishing ground was based on skipper knowledge of catch distribution of the primary target species of the study; *Nephrops*, cod, and plaice. The two cruises therefore differed in vessel, trawl, and catch size, so the results can indicate the sensitivity of the selectivity of the codends to such differences. In both years, the two test codends with covers fished simultaneously in the twin-trawl rig, and to avoid bias attributable to differences in performance between starboard and port trawls, the codends were interchanged throughout the cruises. In all, 24 daylight hauls with each codend design were made (Table 1).

Measuring the catch

To minimize selection at the surface, the covers and codends of both trawls were hauled onto the deck before processing the catch. In 2006, cod, plaice, haddock, and whiting were measured to the centimetre below, and the CL of *Nephrops* to the millimetre below with electronic calipers. We used the midpoints of the length classes in the analyses. In 2007, the number of days at sea was limited, so to optimize the number of hauls, only cod, plaice, and *Nephrops* were measured individually because these three species are the most important in this fishery. *Nephrops* and whiting catches were subsampled when large. Weight of the measured fish and *Nephrops* was estimated using month-specific length–weight conversion factors for fish (Coull *et al.*, 1989) and gender-specific conversion factors for *Nephrops* (ICES, 1995). Total catch weight was taken as the sum of the weight of the measured fish and the weight of the rest of the catch, including debris.

Data analysis

Data from the two cruises were analysed separately. For estimating the selection parameters, data from the upper and the lower covers were summed for each haul of each codend. Estimates were based on unraised data, i.e. including both the raw data and the subsampling ratio. In cases of subsampling of the cover catch, a joint subsampling ratio was estimated for each length group according to the following equation: joint subsampling ratio = *count*/*raised*, where *count* is the total number of sampled animals in the upper and lower cover and the term *raised* refers to the estimated number of animals in the two cover compartments obtained by dividing the *count* in each compartment by the corresponding subsampling ratio, then adding the two estimates.

Initially, CC2000 software (www.constat.dk) was used to analyse the data on haul level. A goodness-of-fit test, referring the deviance to a χ^2 distribution (Wileman *et al.*, 1996), showed that a logistic curve described the data well and that a lack of fit was indicated for one haul only (Table 2). Reasonable numbers

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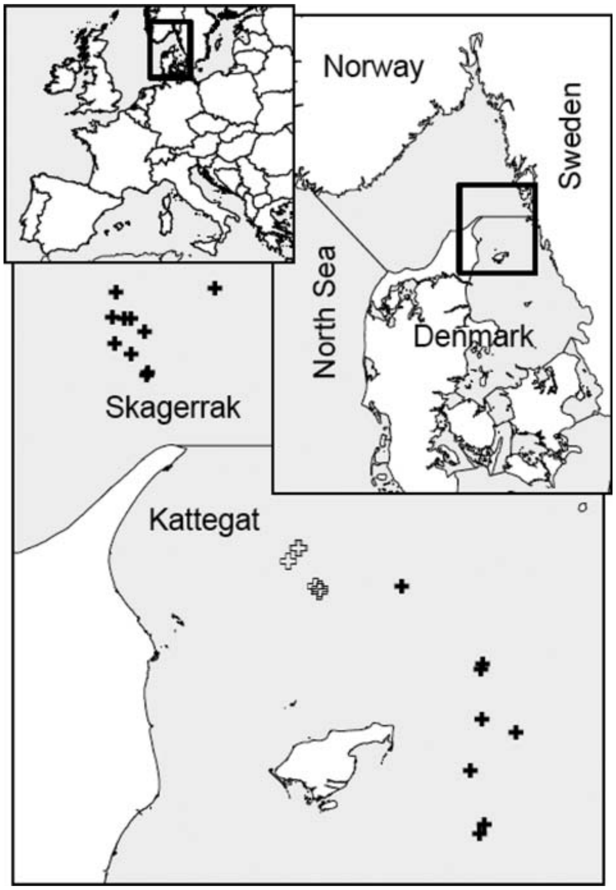

Figure 3. Distribution of hauls in 2006 (black crosses) and 2007 (white crosses). The overview map shows the location of the Danish fishing area.

of all species were caught in most hauls, with plaice in 10 hauls of the 2006 sea trials as the only exception (Table 2). The size distributions of haddock and whiting fitted their selective range in the standard DMC, but not in the standard SMC, and vice versa for *Nephrops*. The few individuals in the selective range resulted in a lack of convergence when analysing data on a haul level (Table 2). Subsequent combination of selection curves using Fryer's model (Fryer, 1991) would therefore not include all available data, so to optimize the use of our data, we used a generalized non-linear mixed model (GNLMM). The method is described by Millar *et al*. (2004), and the complete model includes the between-haul variations of both L_{50} and SR as random variables, and gear type as the dependent variable. In cases where the complete model did not converge, parameters on haul level were inspected to evaluate whether the smallest between-haul variation was on L_{50} or SR. Excluding the between-haul variation on this parameter would always make the model converge. Non-significant effects of gear type on either L_{50} or SR were excluded from the model, and the analysis was run again. The model was fitted with the NLMIXED procedure available in the statistical software package SAS, as prescribed by Millar *et al*. (2004). When comparing L_{50} or SR between the two codends, we used the significance estimates provided by the model. Overlap of the 95% confidence limits of the parameters was used to compare the selectivity of the codends between the two years.

The data were first raised by use of the subsampling ratio, then the direction of escapement was estimated for each haul as the number of escapees retained in the upper compartment divided by the total number of escapees. In cases in which the directions of escapement were normally distributed, the significance of the differences between the two gears was tested with a paired *t*-test. When the test for normality failed, data were instead tested using a Wilcoxon signed rank test. The correlation between direction of escapement and fish length was also tested; data for single length groups were treated as above, but length groups that contained fewer than five animals within a haul were excluded from that haul. Linear regressions based on the least-squares method were used to determine whether the slopes of the regression lines deviated significantly from zero.

Results

In 2006, 18 hauls were conducted, and in 2007 there were 6 hauls (Table 1). In 2006, the duration of haul was limited to about 1.5 h to preclude large catches in the covers. The design of the vessel used in 2007 allowed larger catches to be handled, and the duration of haul was extended to $\sim$3.5 h, which increased the mean catches in the test codends from 184 to 284 kg and from 126 to 309 kg for the standard DMC and the standard SMC, respectively (Table 1). The composition of the catch differed between years (Table 2). By weight, the mean catches of *Nephrops* ranged from 18.5 to 21.5 kg per haul, with no difference between years, whereas catches of cod were $\sim$85% lower in 2007 than in 2006 and catches of plaice were three times higher in 2007. Subsampling ratios of *Nephrops* and whiting ranged from 0.11 to 0.75.

Selection parameters

For the roundfish cod, haddock, and whiting, the NLMIXED model yielded significantly ($p < 0.001$) higher estimates of L_{50} for the standard SMC than for the standard DMC, differences ranging from 9 to 15 cm (Table 3). In 2006, the modelled SR estimates were significantly ($p < 0.05$) higher in the standard SMC for cod and haddock. For whiting in 2006 and cod in 2007, no significant ($p > 0.05$) difference between the estimated SR values for the two gear types was found, so the gear effect on SR was excluded from the NLMIXED model in these cases.

The NLMIXED model yielded significantly ($p < 0.001$) lower estimates of L_{50} for plaice for the standard SMC than for the standard DMC, differences ranging from 4 to 6 cm (Table 3). The reduction in L_{50} corresponds to the difference in mesh size between the codends, so the resulting selection factors (SF = L_{50}/mesh size) are similar (Table 3). A significant ($p < 0.05$) difference in SR estimates between codends was found only in 2007; the estimate of the standard DMC was 1.3 cm greater than that of the standard SMC.

Nephrops were collected both in 2006 and 2007, and estimates are given in Table 3. For both years, the NLMIXED model yielded significantly ($p < 0.0001$) higher estimates of L_{50} for the standard SMC than for the standard DMC. The SR estimates were significantly ($p < 0.01$) higher for the standard SMC in 2007, but there was no significant difference in 2006.

Cod, *Nephrops*, and plaice were measured in both years, and a small increase in the estimated L_{50} was detected for all three species in the standard DMC in 2007 compared with 2006. However, the increase in L_{50} was not significant ($p > 0.05$), nor were the differences in SR between years (Figure 4). For the standard SMC, the

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Table 1. Operational conditions for all hauls in 2006 and 2007 together with mean and standard deviation.

Haul id	Vessel	Date	Latitude	Longitude	Duration (h)	Wave height (m)	Speed (knots)	Wire length (m)	Depth (m)	Door distance (m)	Total catch in test codend (kg)	
											Standard DMC	Standard SMC
1_2006	FN234	9/21/2006	57.5323	11.2361	1:00	0.75	2.6	125	43	85	110	121
2_2006	FN234	9/21/2006	57.4110	11.4523	1:00	0.75	2.6	150	60	85	101	94
3_2006	FN234	9/22/2006	57.4041	11.4464	1:30	0.5	2.5	150	62	85	174	159
4_2006	FN234	9/22/2006	57.3065	11.5369	1:30	0.75	2.6	150	63	86	85	57
5_2006	FN234	9/23/2006	57.3291	11.4442	1:30	1.25	2.6	150	66	85	151	120
6_2006	FN234	9/23/2006	57.2533	11.4085	1:30	1.25	2.6	150	67	85	233	124
7_2006	FN234	9/24/2006	57.1571	11.4269	1:30	0.5	2.6	150	64	85	298	313
8_2006	FN234	9/24/2006	57.1722	11.4413	1:00	0.5	2.6	150	73	86	541	315
9_2006	FN234	9/25/2006	57.9056	10.4538	1:00	0.5	2.6	200	106	86	122	62
10_2006	FN234	9/25/2006	57.8888	10.4997	1:30	0.5	2.6	200	110	86	152	59
11_2006	FN234	9/26/2006	57.9445	10.4492	1:30	0.5	2.6	200	103	85	198	70
12_2006	FN234	9/26/2006	57.9413	10.4999	3:00	0.5	2.6	200	114	85	216	137
13_2006	FN234	9/27/2006	57.9227	10.5380	1:30	0.5	2.6	200	120	86	102	59
14_2006	FN234	9/27/2006	57.9826	10.4606	1:30	0.7	2.6	200	109	86	166	100
15_2006	FN234	9/28/2006	57.9831	10.7382	1:30	0.7	2.6	300	184	86	120	160
16_2006	FN234	9/28/2006	57.9412	10.4822	1:30	0.6	2.6	200	110	87	176	84
17_2006	FN234	9/28/2006	57.8612	10.5442	1:30	0.5	2.6	200	106	87	190	124
18_2006	FN234	9/29/2006	57.8570	10.5409	1:30	0.5	2.6	200	109	87	167	106
				Mean	1:28	0.7	2.6	181.9	92.9	85.8	183.5	125.8
				s.d.	0:26	0.24	0.02	40.04	33.49	0.73	104.09	75.85
1_2007	RS30	8/22/2007	57.5360	10.9973	3:01	1.5	2.5	235	36	100	330	380
2_2007	RS30	8/22/2007	57.5738	10.9231	3:06	1.5	2.6	235	30	101	320	285
3_2007	RS30	8/23/2007	57.5299	11.0084	3:13	0.5	2.6	235	36	100	355	335
4_2007	RS30	8/23/2007	57.5923	10.9539	4:00	0.4	2.6	235	32	98	217	254
5_2007	RS30	8/24/2007	57.5269	11.0066	3:20	0.4	2.6	235	35	98	300	420
6_2007	RS30	8/24/2007	57.5935	10.9502	4:02	0.6	2.6	235	32	100	180	180
				Mean	3:27	0.8	2.6	235.4	33.5	99.5	283.7	309.0
				s.d.	0:27	0.55	0.04	0.00	2.43	1.22	69.30	87.50

only significant ($p < 0.05$) difference in selection parameter estimates between the two years was the L_{50} for *Nephrops*, which was higher in 2006 (Figure 4).

Vertical direction of escapement

Only *Nephrops* and whiting showed a pronounced preference in the direction of escapement in both gears and in all hauls based on all length groups combined (Figure 5). Therefore, depending on codend design, 85.0–93.7% of the *Nephrops* escaped downwards through the lower panel of the codend, whereas 66.8–90.9% of the whiting escaped upwards through the upper panel. For some species, the type of codend had a significant effect on escapement behaviour. Both haddock and whiting showed a significantly ($p < 0.05$) different preference in the direction of escapement in the two codend types. For both species, more fish escaped upwards in the standard SMC (Figure 5).

Plots of the direction of escapement vs. length revealed significant correlations for several species (Figure 6). Although significantly different from zero, the slope of the regression line was negligible (<0.01) usually. However, cod in both codends and haddock, plaice, and whiting in the standard DMC showed a pronounced negative relationship between the length and the direction of escapement. A pronounced positive relationship was found only for haddock and plaice in the standard SMC.

Discussion

Our novel cover design worked well and allowed estimation of both selection parameters and evaluation of the vertical direction of escapement. The relationship between length and preference of direction of escapement was consistent for the entire size range, demonstrating that any migration of small individuals between the two compartments of the cover was minimal. The results demonstrate that the selective properties of a standard SMC and a standard DMC differ significantly, and that the optimum mesh shape is species-specific. The selectivity of the two codends was consistent between trials, with *Nephrops* in the standard SMC being the only exception. Selectivity of *Nephrops* may be affected by the catch composition which, in 2006, was dominated by *Nephrops* and roundfish and, in 2007, by *Nephrops* and flatfish.

The relatively small vessel (characteristic for the fishery) and hence the difficulty in handling the covers restricted the catch weight that could be handled in the experiment. A rough estimate of commercial catch sizes, including discards, can be made from the Danish discard database by extracting data on standard 90 mm codends for the past 5 years. For vessels below medium size (<400 hp), catch weights ranged from 158 to 1400 kg for the Kattegat ($n = 27$, 24 of which were within the range of catches of the standard DMC, 85–541 kg), and from 92 to 1481 kg for the Skagerrak ($n = 50$, 20 of which were within the range of our experiments). The total catch rates obtained in the present study are therefore within the norm for the fishery, and also within the range of results previously reported as being similar to normal

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Table 2. The number of each species caught in the codend/cover (upper+lower). Lack of convergence of the haul-based model is shown by an asterisk (*). A lack of fit ($p < 0.05$) is shown by a double asterisk (**) if the goodness of fit, referring the deviance to a Chi-squared distribution, indicates it.

	Standard DMC					Standard SMC				
Haul	**Cod**	**Haddock**	***Nephrops***	**Plaice**	**Whiting**	**Cod**	**Haddock**	***Nephrops***	**Plaice**	**Whiting**
2006										
1	16/177	387/734	25/5	103/14	172/681	8/258	0/1246*	13/18	115/1	1/907*
2	43/159	143/243	244/10	130/47	187/433	14/391	0/399*	120/119	181/1	0/601*
3	73/289	80/393	1 477/98	151/74	225/394	38/268	3/631	758/927	195/13	0/635*
4	27/82	49/51	1 000/122	15/5	147/270	3/86*	2/112*	365/1 127	10/0*	0/443*
5	70/142	76/162	1 035/178	94/12	238/286	30/238	2/481	458/1 210	89/4	7/895
6	66/358	16/47	302/32	65/4	266/943	56/339	6/65	153/190	60/1	5/1 153
7	98/505	8/9	706/62	103/4	181/1 270	58/517	7/25	443/494	123/1	5/1 646
8	62/169	15/23	94/18	78/6	114/820	54/132	12/50	66/111	104/1	9/1 311
9	137/136	40/61	1 566/68	0/0*	153/14	23/201	4/99*	364/1 273	1/0*	2/150*
10	122/145	37/49	2 317/171	1/0*	108/24	25/172	2/76*	427/2 022	0/0*	2/129*
11	86/100	12/17	5 621/848	0/0*	60/11	29/226	1/36	897/5 075	0/0*	4/99
12	114/165	20/57	2 890/528	0/0*	131/22	45/217	5/53*	811/3 162	0/0*	6/111
13	87/74	23/32	615/80	1/0*	85/17	32/161	3/35	189/495**	0/0*	1/74
14	85/106	44/87	3 317/294	0/0*	104/29	33/186	0/87*	1 142/2 952	0/0*	4/121
15	34/0*	0/0*	28/0*	1/0*	6/1*	32/6	0/4*	14/32	0/0*	0/3*
16	91/95	15/27	4 504/420	1/0*	93/17	26/194	0/46*	1 353/4 004	0/0*	3/128
17	172/235	101/186	1 322/151	1/0*	213/28	47/380	29/283	302/1 012	0/0*	5/203
18	143/139	82/107	207/18	1/0*	349/39	63/210	14/214*	44/158	0/0*	8/515
Total	1 526/3 076	1 148/2 285	27 270/3 103	745/166	2 832/5 299	616/4 182	90/3 942	7 919/24 382	878/22	62/9 124
2007										
1	18/3	Na	2 158/106	90/104	Na	10/30	Na	1 673/1 164	170/9	Na
2	34/2	Na	42/3	147/172	Na	33/29	Na	13/38	268/58	Na
3	37/6	Na	2 519/30	208/107	Na	7/56	Na	1 651/642	181/17	Na
4	9/9	Na	148/4*	100/294	Na	11/62	Na	70/58	321/47	Na
5	18/13	Na	2 570/160	134/209	Na	4/28	Na	2 348/1 182	250/24	Na
6	17/17	Na	56/6	90/269	Na	3/17*	Na	56/42	209/19	Na
Total	133/50	Na	7 493/309	769/1 155	Na	68/222	Na	5 811/3 126	1 399/174	Na

Table 3. Parameter values estimated using the NLMIXED model.

		Standard DMC				Standard SMC			
Species	**Year**	**L_{50} (cm)[a]**	**SR (cm)[a]**	**SF**	**L_{50}/SR**	**L_{50} (cm)[a]**	**SR (cm)[a]**	**SF**	**L_{50}/SR**
Cod	2006[b]	15.03 (14.34 – 15.72)	3.28 (2.59 – 3.98)	1.60	4.58	26.92 (26.24 – 27.60)	4.40 (3.63 – 5.17)	3.80	6.12
	2007[c]	16.86 (14.03 – 19.68)	6.28 (3.63 – 8.93)	1.77	2.68	26.33 (23.77 – 28.90)	6.28 (3.63 – 8.93)	3.85	4.19
Haddock	2006[d]	15.17 (14.66 – 15.68)	3.25 (2.94 – 3.56)	1.62	4.67	26.30 (25.15 – 27.44)	4.07 (3.48 – 4.67)	3.72	6.46
Nephrops	2006[c]	16.71 (14.66 – 18.76)	14.71 (13.27 – 16.15)	0.18	1.14	41.18 (39.17 – 43.20)	14.71 (13.27 – 16.15)	0.58	2.80
	2007[d]	18.35 (12.44 – 24.25)	11.73 (9.21 – 14.23)	0.19	1.56	31.00 (26.31 – 35.69)	17.90 (14.89 – 20.91)	0.45	1.73
Plaice	2006[e]	19.07 (18.30 – 19.84)	3.45 (2.90 – 4.00)	2.03	5.53	14.61 (13.34 – 15.88)	3.45 (2.90 – 4.00)	2.06	4.23
	2007[b]	19.76 (18.93 – 20.59)	3.60 (2.85 – 4.35)	2.08	5.49	13.89 (12.98 – 14.79)	2.34 (1.58 – 3.11)	2.03	5.94
Whiting	2006[e]	18.10 (17.28 – 18.92)	3.61 (3.43 – 3.79)	1.93	5.01	33.47 (32.47 – 34.46)	3.61 (3.43 – 3.79)	4.73	9.27

SF = L_{50}/(measured mesh size × 1.04), where 1.04 is the approximated conversion factor between the ICES gauge and the EU wedge (Ferro and Xu, 1996). Data in parenthesis are the 95% confidence limits.
[a]Estimates for *Nephrops* are in mm.
[b]Complete model including gear effect and between-haul variation on both SR and L_{50}.
[c]Model including gear effect on L_{50}. and between-haul variation on both SR and L_{50}.
[d]Model including gear effect on SR and L_{50} but between-haul variation only on L_{50}.
[e]Model including gear effect and between-haul variation on L_{50} only.

practice in the Swedish *Nephrops* fishery (Valentinsson and Ulmestrand, 2008). Our results are therefore considered to be representative of smaller vessels in *Nephrops*-directed fisheries. However, this restriction in representativeness may change soon with the implementation of highly selective devices, such as grids (Catchpole *et al.*, 2006; Valentinsson and Ulmestrand, 2008; Frandsen *et al.*, 2009) and escape windows (Madsen *et al.*, 2010). These additional devices are expected to reduce the codend catch weight substantially, and they have already been enforced seasonally in part of the Kattegat, to protect the cod stock.

Selection parameters

Selection factors (SF = L_{50}/mesh size) can be used to compare our results with the results of previous experiments on *Nephrops*-directed fisheries. As twine thickness influences the selectivity of a codend (Lowry, 1995; Herrmann and O'Neill,

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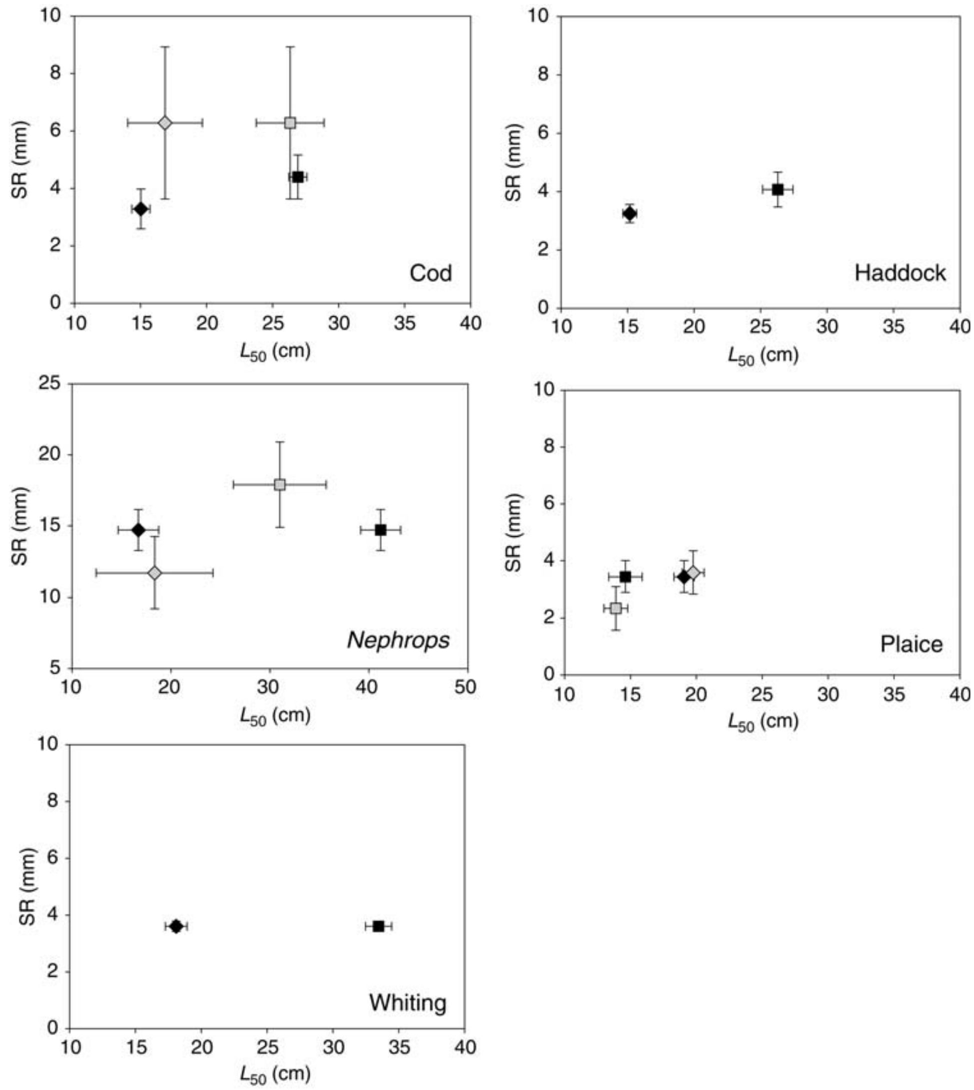

Figure 4. Parameter estimates for different species obtained using the NLMIXED model. Black symbol, 2006 data; grey symbol, 2007 data; squares, standard SMC; diamonds, standard DMC. Error bars indicate the 95% confidence limits around the mean.

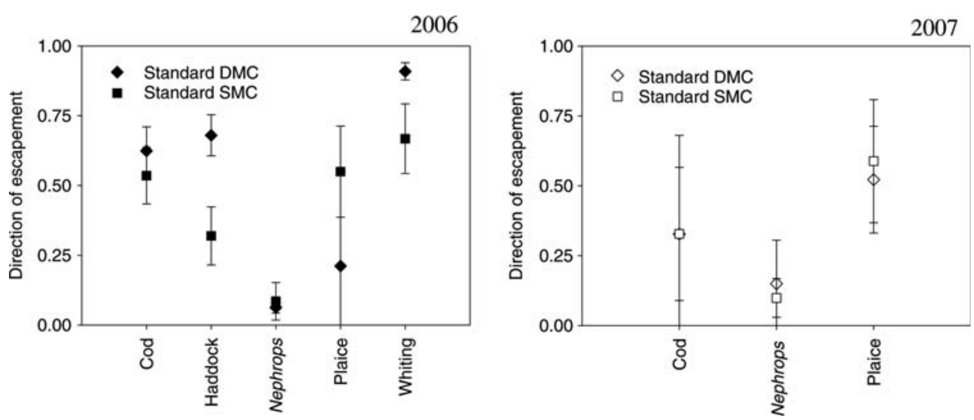

Figure 5. Vertical direction of escapement in 2006 and 2007. Estimates are based on raised data summed over all length groups. For each haul, the direction of escapement was estimated as the fraction of escapees retained in the upper cover. The symbols illustrate the means of all hauls, and the error bars show the 95% confidence limits.

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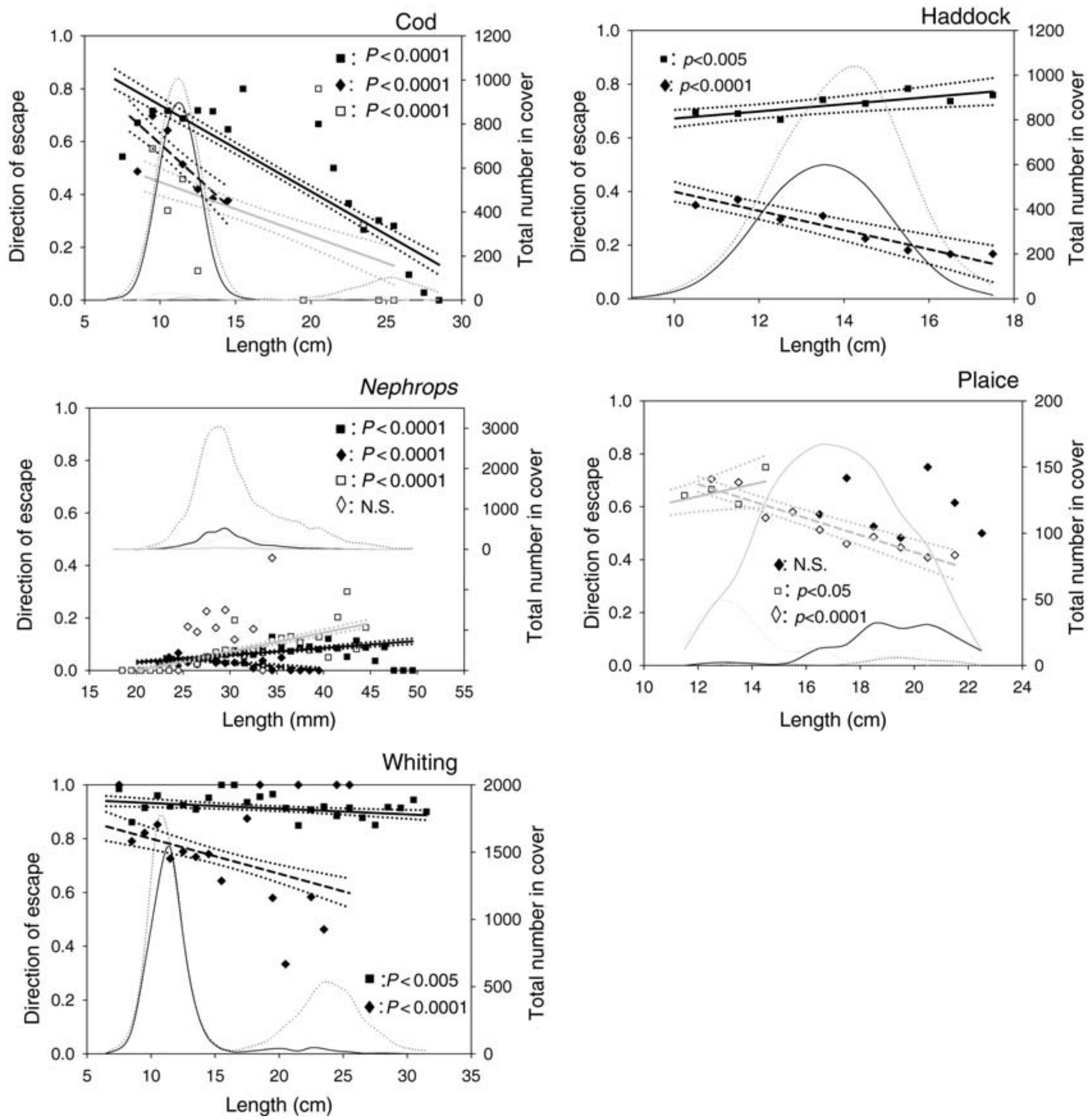

Figure 6. Relationship between the vertical direction of escapement and length (left *y*-axis) and length distribution of fish retained in the cover (right *y*-axis). For each length group, the direction of escapement was estimated as the fraction of escapees retained in the upper cover (squares and diamonds), and the regression lines based on the data at a haul level were estimated (bold lines), with standard SMC, squares and solid lines; standard DMC, diamonds and broken lines; dotted lines, the 95% confidence band of the regression; 2006, black symbols and black lines; 2007, white symbols and grey lines. Statistics on the slope of the regression are given. N.S., no significant deviation from zero. Numbers retained in the cover are shown as thin lines, with standard SMC, dotted lines; standard DMC, solid lines; 2006, black lines; 2007, grey lines.

2006), only experiments testing codends made of netting reasonably similar to that tested here were used when evaluating the estimated selection parameters.

The SF values for cod, haddock, *Nephrops*, plaice, and whiting in the standard DMC were all low compared with the SF estimates reported previously (cod, 2.4; haddock, 2.4–2.6; *Nephrops*, 0.28–0.38; plaice, 2.3; whiting, 2.7; Madsen *et al.*, 2008; Frandsen *et al.*, 2009). Small catches limit the opening of diamond-meshes and result in lower estimates of L_{50} (O'Neill and Kynoch, 1996; Herrmann, 2005), and this effect may be increased by the thick double twine used in this experiment. Although catches increased by >50% in 2007, they were still at the lower end of catches evaluated by the studies referred to above. The mean catch weights of those studies ranged from 300 to 393 kg. Based on simulations, it is predicted that an increase in catch weight from ~170 to ~290 kg in a diamond-mesh codend (100 mm, 100 meshes around) will lead to an increase in the L_{50} of haddock by 4–5 cm, whereas a catch increase from 170 to ~500 kg may increase the L_{50} of haddock by as much as 10 cm (Herrmann, 2005). The increase in catches in the standard DMC from 2006 to 2007 did not result, however, in a significant ($p > 0.05$) increase in the L_{50} of any of the three species that we measured in both years.

For the standard SMC, comparable selection estimates are available for *Nephrops* only. The SF estimate for *Nephrops* in the standard SMC was within the range of the earlier studies (*Nephrops*, 0.40–0.63; Larsvik and Ulmestrand, 1992; Stergiou *et al.*, 1997; Campos *et al.*, 2002; Bahamon *et al.*, 2006; Sala *et al.*, 2008; Sala and Lucchetti, 2010).

In general, the standard SMC yielded higher estimates of L_{50}/SR for all roundfish species and *Nephrops* than did the standard

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DMC. For these species, therefore, an increase in L_{50} is not associated with a proportional increase in SR, and the standard SMC hence has better selective properties for roundfish and *Nephrops*. In contrast, plaice gave the highest estimates of L_{50} in the standard DMC; SF values of the two codends were, however, comparable. The standard DMC was expected to have better selective properties for plaice, but the relatively soft and thin netting (3 mm polyamide vs. 2×5 mm polyethylene) of the standard SMC, in combination with the relatively small catches, may explain why the difference between the two codends was not pronounced in the present experiment.

Vertical direction of escapement

In line with the results of previous investigations (Hillis and Earley, 1982), *Nephrops* escaped almost exclusively through the lower panel of the codend. Interestingly, the only fish species that exhibited a distinct preference in the direction of escapement was whiting, which primarily escaped upwards. Haddock, which has previously been shown to stay high in the extension piece (Krag *et al.*, 2009a), and escape through square-mesh windows in the top panel of the codend (Madsen *et al.*, 1999; Graham *et al.*, 2003, Frandsen *et al.*, 2009), only showed this preference in direction of escapement in the standard SMC; haddock caught in the standard DMC tended to escape downwards.

The swimming speed of fish is size-dependent (Breen *et al.*, 2004), so because the fish escaping from the codend are small, their ability to navigate within the trawl cavity could be expected to be limited. However, the maximum sustainable swimming speed of a haddock 16 cm long is 0.8 knots (Breen *et al.*, 2004), and at a towing speed of 2.9 knots, water flow in a partially fish-filled codend has been found to range from 0 to 0.6 knots (Main and Sangster, 1981). On the basis of this knowledge, we assume that a pronounced direction of escapement, at least for the larger escapees, reflects a species-specific preference.

The differences between the observed preferences in terms of direction of escape in this and in previous work are not necessarily contradictory, because the present setup did not include an alternative escape route, as do experiments with square-mesh panels. It is likely that introducing such a selective device in the standard DMC would alter the preferred direction of escape of species such as haddock, for which behaviour has previously been shown to be influenced by visual cues (Glass and Wardle, 1989).

The natural behaviour of most fish is to stay clear of netting, and this natural avoidance response can be modified by manipulating the visual stimulus presented by the netting panel (Glass *et al.*, 1993). The contrast of the netting used for the two codends is expected to be different, because the standard DMC is constructed of dark (green) heavy (2×5 mm) twine, whereas the standard SMC is made of white thinner (1×3 mm) twine. All fishing was conducted during daylight, so we assume that the standard SMC presented a lower contrast in the light from the surface and may therefore appear a more attractive escape route. Rather than the difference in mesh shape, these factors may explain the different behaviour of some of the species in the standard SMC and the standard DMC.

Length-dependent differences in vertical preference of fish in trawls have been observed for several species, including haddock, cod, whiting, and plaice (Holst and Revill, 2009; Holst *et al.*, 2009). In our study, cod in particular exhibited a pronounced length-dependence, with small fish escaping upwards and larger fish escaping downwards. This is in contrast to the behavioural pattern found farther forward in the trawl (Holst and Revill, 2009; Holst *et al.*, 2009). However, those studies investigated larger fish, so the slope of the regression lines is not comparable with those found here.

Conclusions

The results of our study have confirmed the belief that the selectivity of the conventionally used standard DMC is poor, and they further suggest that this is particularly so in the cases of small catches and relatively thick double twine. Owing to the relatively small catches, the outcome of this study is most applicable to *Nephrops*-directed fisheries under similar conditions. In future, such conditions are probably to result from implementation of highly selective devices that are expected to reduce the codend catch weight substantially.

The selective properties of the 70 mm standard SMC are significantly better for *Nephrops* and roundfish than those of the 90 mm standard DMC. The use of a standard SMC is therefore expected to reduce discards of these species significantly. However, the estimated selection parameters for *Nephrops* in the standard SMC demonstrate that using a mesh size of 70 mm would result in loss of legal-sized (>40 mm CL) catch. In terms of plaice, the selectivity of the 70 mm standard SMC is more in conflict with the regulations on MLS (27 cm) than the selectivity of the 90 mm standard DMC. The use of a standard SMC would therefore be expected to increase the discarding of that species.

The positive effect of combining mesh shapes has previously been attained by inserting square-mesh windows in diamond-mesh codends, but the aim of those gears was primarily to reduce the discarding of roundfish. The results of the present study demonstrate the potential benefits of combining different nettings in the codend to improve the selectivity of a wider range of species in mixed-species fisheries.

Our study has shown that only whiting and *Nephrops* have a strong preference to escape either from the upper or the lower panel. For those species, an additional escape panel with an optimized netting configuration would theoretically influence the selectivity only if it is placed in their preferred direction of escapement. For all other species, we would expect such a panel potentially to improve the selectivity of the codend, irrespective of its vertical position. However, the behavioural patterns in the codend may be altered by the visual cues introduced when different nettings are combined. Further studies of such composite codends, designed to optimize multispecies selectivity by exploiting differences in behaviour and morphology, are therefore needed. Such studies should also take the length-dependent differences in behaviour into account.

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Paper IV

Development of a codend concept to improve size selectivity of *Nephrops* (*Nephrops norvegicus*) in a multi-species fishery

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Abstract
Species-specific differences in morphology and minimum landing size will often result in high discard rates in mixed-species fisheries. This is the case in the Danish *Nephrops*-directed fishery and the aim of this study was to improve the size selectivity of *Nephrops* without increasing catch below minimum landing size (MLS) of cod (*Gadus morhua*) and plaice (*Pleuronectes platessa*). A new codend concept combining square meshes and diamond meshes in a four-panel configuration was developed and tested in the Kattegat and Skagerrak. A 5 m long 70 mm square-mesh panel was inserted in the lower panel of the codend to increase size selectivity of *Nephrops* while the remaining three panels were made of standard 90 mm diamond-mesh netting to maintain selectivity of plaice and cod. The concept succeeded in significantly ($p < 0.0001$) increasing L_{50} of *Nephrops* without increasing discards of either plaice or cod. When using the new codend concept, expected numbers of *Nephrops* below MLS (carapace length = 40 mm) were reduced by approximately 37% but the expected weight of marketable catch was also reduced by 21%.
The concept was further optimized and tested in a second experiment to meet commercial viability. This experiment indicated that size selectivity of *Nephrops* could be adjusted by changing the square-mesh panel but differences in mean selection between the gears were insignificant. We introduce a new analytical approach with increased statistical power to detect differences in selection parameters between different codends.

Keywords: Selectivity, Square-mesh panel, *Pleuronectes platessa, Gadus morhua*, *Nephrops norvegicus,* Trawl, Mixed species fishery

1. Introduction

The Danish *Nephrops*-directed fisheries in the Kattegat and Skagerrak are conducted using bottom trawls with a 90 mm diamond-mesh codend. *Nephrops* (*Nephrops norvegicus*) is economically the most important species targeted in Kattegat and Skagerrak (based on landings in 2009, Ministry of Food, Agriculture, and Fisheries, The Danish Directorate of Fisheries). It is a mixed-species fishery and besides *Nephrops*, catches consist of several species of fish, including cod (*Gadus morhua*) and plaice (*Pleuronectes platessa*) which also constitute an important part of the economy. Relatively small meshes are needed to retain the *Nephrops* and this can result in high discard rates of both target and non-target species (e.g., Frandsen et al., 2009). Development of more selective fishing gear for this fishery have focused on reducing the discard of cod (Frandsen et al., 2010b; Krag et al., 2008; Madsen and Stæhr, 2005; Madsen et al., 2010; Valentinsson and Ulmestrand, 2008) whereas the discards of flatfish (e.g., plaice) and *Nephrops* have received less attention. The aim of this study was to improve codend selectivity of *Nephrops* without increasing discard of either cod or plaice.

Currently, the Skagerrak and Kattegat *Nephrops* stocks are exploited at a sustainable level (ICES, 2010a). However, in recent experiments with commercial trawls, more than 50% by number of *Nephrops* caught were below the minimum landing size (MLS) of 40 mm carapace length (CL) (Frandsen et al., 2009; Krag et al., 2008). Survival of the discarded *Nephrops* varies greatly (12–85%) depending on temperature, salinity, and handling time (Castro et al., 2003; Evans et al., 1994; Harris and Ulmestrand, 2004), and the ICES Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak uses a figure of 25% survival (ICES, 2010b). Compared to this value, survival of *Nephrops* that escape during the fishing process is high, approximately 82% (Wileman et al., 1999). Thus, making the fishing gear more size-selective with regard to *Nephrops* should increase the overall survival of undersized individuals.

Compared to that of fish in general, the slope of the selection curve for *Nephrops* is more flat (Briggs, 1986), and unless this slope is increased, a reduction in discards (i.e., by increasing mesh size) will result in an increased loss of legal-sized *Nephrops*. To improve size selectivity of this species, the aim was thus to adjust length of 50% retention (L_{50}) to better match the MLS of 40 mm carapace length (CL) and to minimize the relative slope (i.e. the selection range ($SR = L_{75} - L_{25}$) divided by L_{50}) of the selection curve for *Nephrops*. As these means will reduce discards and minimize commercial losses we refer to them as improvements of size selectivity.

A study based on stochastic modeling has showed that the relatively high *SR* values found for *Nephrops*, to some extent, can be explained by variation in mesh geometry along the codend (Frandsen et al., 2010a). Such variation is characteristic for diamond-mesh codends where drag from the catch build-up closes all but a few rows of meshes just in front of the catch accumulation (Wileman et al., 1996). The forces are distributed differently in square meshes which stay more open along the entire length of the codend and the mesh geometry of this type of netting is therefore more uniform (Robertson and Stewart, 1988). This is important for the size selection of *Nephrops* which can take place along the entire length of the codend if the mesh configuration allows it (Frandsen et al., 2010a)

Currently, the Swedish *Nephrops* fleet uses a 70 mm square-mesh codend in combination with a grid, and this codend has been proven to work well in this single-species fishery (Valentinsson and Ulmestrand, 2008). In a multi-species fishery as the one investigated in this study, the 70 mm square-mesh codend is, however, expected to retain more juvenile plaice below MLS (27 cm) than a standard 90 mm diamond-mesh codend as it has a significantly lower L_{50} for this species (Frandsen et al., 2010b). In general, square meshes have good selective properties for round fish (Frandsen et al., 2010b; Halliday et al., 1999; Robertson and Stewart, 1988), whereas diamond meshes may be better suited for size selection of flatfish (He, 2007; Madsen and Valentinsson, 2010; Walsh et al., 1992). One single mesh configuration is therefore not appropriate if size selectivity of *Nephrops*, cod, and plaice is to be considered simultaneously in the same codend.

Therefore, in multi-species fisheries, composite codends constructed of a combination of square-mesh and diamond-mesh netting in the appropriate positions may be able to provide improved size selectivity of multiple species in the same codend. Cod and plaice have been found to escape both upwards and downwards through the codend meshes, whereas *Nephrops* escape almost exclusively through the lower panel (Frandsen et al., 2010b; Hillis and Earley, 1982; Krag et al., 2009). This is in line with visual observations of *Nephrops* rolling along the lower sheet of netting (Briggs and Robertson, 1993; Main and Sangster, 1985; Robertson and Ferro, 1991).

Based on the species-specific escapement patterns and selective properties described above, a four-panel codend concept combining diamond- and square-mesh netting was developed and tested in the Danish *Nephrops*-directed fisheries in the Kattegat and Skagerrak. The experimental work was conducted in two steps: first, the new concept was tested against a conventional codend and subsequently, the concept was optimized with regards to commercial conditions.

A new analytical approach was developed to increase the statistical power for estimating the difference in selection parameters between the gears tested in the first step.

2. Methods

2.1. Development of the codend concept

We took the differences in species-specific escapement patterns (Frandsen et al., 2010b) and morphology (Frandsen et al., 2010a) into account when designing the codend. Therefore, to improve selection of *Nephrops*, a 5 meter long section of square-mesh netting was inserted in the lower panel of a four-panel configuration made of traditional diamond-mesh netting (Fig. 1). The idea behind the concept is that the large area of square meshes in the bottom panel is optimised with regards to the selectivity of *Nephrops* while the top and sides of the codends are made of standard diamond-mesh netting to maintain the selectivity of plaice and cod.

Compared to a standard diamond-mesh codend constructed of two panels, the extra selvedges in the four-panel design make the orientation of the codend more stable thus allowing a better control of what is up and down. Also, the extra selvedges can absorb a considerable amount of the longitudinal forces that act in the codend and are caused by the drag on the catch build-up. In standard two-panel diamond-mesh codends, these forces tend to close the meshes. Due to this absorption, the geometry of the diamond meshes in the four-panel design is expected to be more uniform throughout the tow and the design has the potential of improving the size selectivity of plaice and cod compared to a standard diamond-mesh codend.

2.2 Deployment of the concept to construct codends for the specific fishery

Two different codend designs based on the concept were tested in the present study (Fig. 2); *Design 1* was the prototype with the sides and the top made of the same 90 mm diamond-mesh netting as that used in commercial codends in the Danish *Nephrops* directed fishery in the Kattegat and Skagerrak while the bottom panel was made of square-mesh netting similar to that used in Swedish square-mesh codends (70 mm nominal mesh size). A standard 90 mm two-panel diamond-mesh codend was used as reference and the setup allowed us to evaluate the concept both against the standard diamond-mesh codend and against literature values for a plain square-mesh codend (Frandsen et al. 2010b).

Before sea trials, *Design 1* was checked in the Hirtshals flume tank and its orientation was found to be stable (Fig. 1). After testing *Design 1* at sea it was found that adjustments were needed to make the design commercially viable; selectivity of *Nephrops* needed modifications and durability of the square-mesh netting needed attention. Fishermen and a netmaker were involved in the development process of *Design 2*. In this design, mesh size of the square-mesh panel was reduced to nominal 60 mm and heavier netting was used. The remaining parts of the codend were left unchanged. *Design 2* was tested at sea using the same vessel and experimental methods.

2.3 The fishing area, vessel, and trawls

The codends were tested in the Kattegat and Skagerrak (Fig. 3). The same vessel, the 386 kW stern trawler RS30 *Mette Amalie* was used to conduct two experiments; the first was conducted in June 2007 (Exp 1) and the second in September 2007 (Exp 2). In both experiments, *Mette Amalie* was rigged for twin trawling, and the trawls were combined fish and *Nephrops* trawls. A three-warp towing system equipped with a 550 kg chain clump and two 194 cm Welle otter boards was used to tow the gear. Choice of fishing grounds was based on skippers experience to find areas that reflect commercial conditions.

2.4 The codend and the net covers

The selectivity of the codends was estimated using the covered-codend method (Wileman et al., 1996). The covers were made of knotted PE netting with a nominal mesh opening of 35 mm (measured mesh size ± 2 S.E.: 35.6 ± 0.71 mm) (Fig. 4). To limit the visual contrast, the cover netting in the region around the codend was made of thin (1.2 mm) white Dyneema® netting oriented to form square meshes, and a zipper was inserted in this section to ease emptying of the test codend. A combination of kites, chains, and floats was used to keep the covers open. The kites were used as described by Madsen et al. (2001).

Three different codends were tested; a 90 mm standard diamond-mesh codend (*DMC*) as the reference, and the two different four-panel codends: *Design 1* and *Design 2* (Fig. 2). All codends were 99.5 meshes long, and they were joined to 3 m long diamond-mesh extensions made of two panels of nominal 90 mm 4 mm double-twine PE *Euroline.* The *DMC* was constructed of two panels of the same material as the extensions. *Design 1* and *Design 2* were both constructed of four panels likewise made of 90 mm 4 mm double-twine PE *Euroline*. A 5 m panel of square-mesh netting (actual length varied from 4.75 to 5.00 m) was inserted in the lower of the four panels, and it terminated four meshes from the codline. The twin-trawl setup allowed simultaneous testing of two different codends. During Exp 1, the *DMC* was tested against *Design 1*, and two identical *Design 2* codends were tested in Exp 2.

Codends and covers were measured in dry condition before trials and in the wet condition after trials using an OMEGA mesh gauge (Fonteyne et al., 2007).

2.5 Data collection and analysis

To follow commercial procedures and avoid additional selection at the sea surface, all covers and codends were hauled on deck before the processing began. Total weight of the codend/cover fraction was obtained using a crane scale on deck. Cod and plaice were measured to the centimeter below and *Nephrops* CL was measured to the millimeter below using an electronic caliper. In the subsequent analysis, 0.5 cm was added to all length classes of fish and 0.5 mm was added to all length classes of *Nephrops*. *Nephrops* were subsampled when catches were large. Weight of fish and *Nephrops* was estimated using length-weight conversion factors (Coull et al., 1989; Frandsen et al., 2010a).

The use of covers on both sides of the twin-trawl rig resulted in two sets of covered codend data for each haul. Thus, for each length class we had data on catches in four compartments: test codend (gear A); cover (gear A); test codend (gear B); and cover (gear B). In Exp 1, gear A was the *DMC* and gear B was the *Design 1* codend.

In Exp 2, gear A and gear B were both the *Design 2* codends. The twin-trawl setup allowed a *pairwise* analysis of data, which boosted the statistical power in detecting differences in size selection between gears tested in parallel. We expected the different gears to display differences in between-haul variation in the size selection process. Therefore, the data sets for the different gears were analyzed independently when estimating the selection parameters to enable the estimation of gear-specific between-haul variation. This approach is similar to the one described and applied by Madsen et al. (2002).

2.5.1 Estimation of selection parameters

Covered-codend data for each type of gear were analyzed separately with the commonly used two-stage procedure (Wileman et al., 1996). In the first stage, logistic curves were fitted to the experimental data on haul level using standard maximum likelihood estimation. If fit statistics indicated that it was unlikely that the logistic curve would be able to describe the experimental data, another type of selection curve would be used (see Wileman et al., 1996 for details). In the second stage, all the selection parameters and their co-variances on haul level were combined to obtain the mean selection curve and the between-haul variation in the parameters describing the mean curve. The analyses in the second stage follow the procedure described by Fryer (1991), which is based on the assumption that the results from single hauls are samples from a multivariate distribution describing the between-haul variation in the selection process. This stage also included an investigation of the total codend catch as a linear fixed effect on the selection process.

The variances for the retention rates for different parts of the mean selection curve were approximated from the values and covariance of the mean selection parameters using the delta theorem (Lehmann, 1983). The approximated variances for the entire selection curve were used to estimate the 95% confidence bands, which subsequently were used to identify length ranges with significant deviations in size selection between gears. All analyses were performed using the software tool SELNET (developed by the second author of this study), which is designed for analysis of codend selectivity data.

2.5.2 Estimation of expected discards and losses

Fryers mean selection curve (Fryer, 1991) which is used to describe selectivity of the different codends gives an estimate of how the gears are most likely to perform in a single haul. Size selection is subject to a between-haul variation which is routinely estimated when estimating the mean selection curve and the density function for the between-haul variation is quantified in the D-variance matrix (Fryer, 1991). This matrix can be used to estimate the expected retention curve for a group of hauls using the same codend while taking the between-haul variation into account. The expected retention curve thus gives an estimate of how the gear is expected to perform on average for a series of hauls and it is therefore appropriate for estimating the expected catches which can be used to evaluate the effect of a gear change.

The expected retention rate is estimated by integrating the retention rate times its density function for the between-haul variation over all possible values of the selection parameters. This procedure avoids over- or underestimation of discards and losses, which otherwise could occur if the retention was based on Fryers mean selection curve without considering the effect of between-haul variation in the selection process. It is our experience that this curve often has a higher *SR* than the mean selection.

The expected discard rates (ED) based on number of individuals below MLS and the expected landing rates (EL) based on weight above MLS (assuming that all individuals below and above MLS are discarded and landed, respectively) were estimated for each type of gear using the length distributions of the fished population and the expected retention rate summarized over length classes below and above MLS as follows:

(1)

$$\mathrm{ED} = \frac{\sum_{l_i=0.5}^{l_i< MLS}\left\{c(l_i)\times r(l_i)\right\}}{\sum_{l_i=0.5}^{l_i<MLS} c(l_i)}$$

$$\mathrm{EL} = \frac{\sum_{l_i=MLS}^{l_i< \infty}\left\{c(l_i)\times w(l_i)\times r(l_i)\right\}}{\sum_{l_i=MLS}^{l_i<\infty}\left\{c(l_i)\times w(l_i)\right\}}$$

where $c(l_i)$ is the total number of individuals in a length group i; $r(l_i)$ is the expected retention rate of individuals in this length group; and $w(l_i)$ is the expected weight of an individual belonging to the length group. In this study, the length distributions of all measured species differed significantly (*F*-test: $p<0.05$, Mann-Whitney *U*-test: $p<0.001$) between the two experiments (Fig. 4), resulting in different $c(l_i)$ values. Therefore, we considered the expected catch compositions separately. The estimates of expected discards and landings are thus based on the length distribution in the fished population and they should not be extrapolated to other fisheries.

2.5.3 Comparing selectivity between gears

Our experimental setup (covered codends fished in a twin trawl configuration) allowed us to clear the data of the bulk of variance components that are haul specific (e.g., time of day, fishing ground, sea state, towing speed, and other environmental and operational factors that vary between hauls), and therefore expected to affect the selectivity of the two trawls equally. Thus, when investigating differences between the two gears fished in parallel, the pairwise nature of the data collection was fully exploited by use of function 2. This function was minimized, which is equivalent to maximizing the likelihood for the observed data:

(2)

$$-\sum_{l}\left\{n_{TA_l}\times\ln\left(\frac{r_A(l)\times q_{TA}}{r_A(l)\times q_{TA}+(1.0-r_A(l))\times q_{CA}}\right)+n_{CA_l}\times\ln\left(1.0-\frac{r_A(l)\times q_{TA}}{r_A(l)\times q_{TA}+(1.0-r_A(l))\times q_{CA}}\right)\right.$$
$$\left.+n_{TB_l}\times\ln\left(\frac{r_B(l)\times q_{TB}}{r_B(l)\times q_{TB}+(1.0-r_B(l))\times q_{CB}}\right)+n_{CB_l}\times\ln\left(1.0-\frac{r_B(l)\times q_{TB}}{r_B(l)\times q_{TB}+(1.0-r_B(l))\times q_{CB}}\right)\right\}$$

where *A* and *B* denote the two gears tested in parallel; *l* is length; *q* is the subsampling ratio; *T* and *C* refers to the test codend and the cover respectively; *n* is number measured; r_A and r_B are retention functions for the two gears described by the parameters L_{50A}, SR_A, L_{50B}, and SR_B; *ln* is the natural logarithm. Expressing the L_{50} estimate for gear *B* relative to that of gear *A* ($L_{50B} = L_{50A} + \Delta L_{50A\rightarrow B}$), and likewise for *SR*, results in the estimation of four parameters (L_{50}, *SR*, ΔL_{50}, and ΔSR) and a 4x4 covariance matrix for each haul. We refer to this method as the *pairwise* analysis.

The standard method for comparing selection parameters between different gears includes only $L_{50,}$ *SR*, and 2x2 covariance matrices, and when combining estimates on haul level, gear is included in the model as a fixed effect. The standard method could not take advantage of the pairwise nature of the data for the two gears, and the power in the analysis would therefore be more affected by between-haul variation in the selection process. The output from our *pairwise* analysis is the numeric difference between the mean selection parameters (i.e., ΔL_{50} and ΔSR) of the two gears as well as the p value for these values to be different from zero.

The *pairwise* method is used to compare the selective properties of *Design 1* and the *DMC* and also to check for differences between the two "identical" *Design 2* codends tested in Exp 2. To compare the parameter estimates of gears tested in different experiments, i.e., *Design 2* with those of the *DMC* and *Design 1,* we use the 95% confidence bands of the mean estimates. Alternatively, the gears could have been analyzed in the standard method by including gear type as a fixed effect as described above. However, since the gears were tested under different conditions e.g. different season and depth and since such an analysis would assume that the between-haul variation in the selection process was similar during the two experiments, we prefer not to combine them in a single model.

3. Results

Fourteen valid hauls were conducted with the *DMC* and *Design 1* during Exp 1. In Exp 2, five hauls were conducted with two identical *Design 2* codends which resulted in a total of 10 hauls for this codend (Table 1). Codend catches ranged from 80 to 1020 kg, with means of 356 kg, 248 kg, and 230 kg for the *DMC*, *Design 1*, and *Design 2*, respectively (Table 2). The total number of individuals retained by the codends and covers were high in both experiments (Table 2). The fished areas and depths in the Kattegat and Skagerrak are commercially exploited and are characteristic in having high abundances of juvenile fish and relatively small *Nephrops* (Fig. 4).

3.1 Codend selectivity

Fit statistics indicated that the logistic curve could be used (Wileman et al., 1996) to describe data with regard to selectivity of the test codends, and selection parameters were estimated for all hauls and species (Table 3). The subsampling ratio of *Nephrops* ranged from 0.09 to 1.0.

Table 4 lists the Fryer mean selection parameters for the three types of gear used in this study. Catch size did not have a significant effect ($p > 0.05$) on L_{50} or *SR* for any gear or species (Table 4). Catch size was therefore excluded from the analysis and the models were re-run. When plotting L_{50} estimates on haul level for gears fished simultaneously, we found that relatively high estimates for gear A were accompanied by relatively high estimates for gear B regardless of codend type (see section 2.5)(Fig. 5). This indicates that haul-specific variation has an effect on the selectivity, and the *pairwise* analysis will therefore be appropriate for investigating differences between these gears (Table 5). The *pairwise* analysis detected the same significant differences between the parameters as did the standard method (codend design modeled as a fixed effect). However, the p values for the differences decreased 100- to 10000-fold for L_{50} and 10-fold for *SR* when using the *pairwise* analysis, thus increasing the significance of the result.

The two identical *Design 2* codends were fished in parallel during Exp 2, and the *pairwise* analysis was used to test for significant differences in the selection parameters between the two codends. In one case, a significant ($p = 0.038$) difference was found between the two gears for the L_{50} of plaice. However, this difference was small (0.5 cm), and because the gears were supposed to be identical, this minor difference was disregarded. All haul estimates for the two *Design 2* codends were combined in the standard Fryer analysis; in this way, any marginal difference between the two gears would be included in the estimates as an increase in the estimated between-haul variation represented in the D-variance matrix.

For ***Nephrops***, *Design 1* had a significantly higher estimate (*pairwise* analysis; $p < 0.0001$) of mean L_{50} (L_{50} = 34.58 mm) than did the *DMC* (L_{50} = 23.99 mm) (Table 4, Table 5). Mean *SR* estimates showed the same tendency, but the increase from the *DMC* (*SR* = 14.67 mm) to *Design 1* (*SR* = 19.58 mm) was smaller than that for the L_{50}, which resulted in a lower SR/L_{50} for *Design 1* (Table 4). Below 21 mm CL, the number of individuals caught was very small (Fig. 4). In this size range, the selection curves for *Nephrops* are therefore not based on experimental data and should be disregarded. The mean L_{50} (29.54 mm) for *Design 2* was between those of the other two gears and overlap of the 95% confidence bands indicated that it was not significantly different from either of these (Table 4, Fig. 6).

A significantly lower retention of *Nephrops* between 23-75 mm CL when using the *Design 1* compared to the *DMC* (Fig. 6) results in a 36% reduction in the expected discard rate (Table 6). The reduction in discard is accompanied by an expected loss in catches above the MLS of 21–22%, depending on the length distribution on which the estimation is based (Table 6).

In the *DMC*, mean L_{50} and mean *SR* for **cod** were estimated to be 21.43 cm and 6.96 cm, respectively (Table 4). The *pairwise* analysis indicated that the selectivity was significantly ($p < 0.01$) improved in *Design 1*, which had a higher L_{50} (L_{50} = 26.10 cm) and a smaller *SR* (*SR* = 5.29 cm) (Table 4, Table 5). The estimates obtained for *Design 2* lie between those for the *DMC* and *Design 1* (L_{50} = 22.52 cm, *SR* = 4.34 cm), and its 95%-confidence bands overlap with these gears (Table 4, Fig. 6) indicating no significant difference between the gears.

Compared to the *DMC*, *Design 1* had significantly lower retention of cod for lengths between 12 and 28 cm indicated by no overlap of the 95% confidence bands for the retention rates (Fig. 6). This length range almost covers the peaks of juvenile fish caught in both experiments (Fig. 4). The reduced retention resulted in a 50–60% reduction in the expected discard rate (Table 6).

The codend design had no significant influence on L_{50} or *SR* for **plaice** (*DMC* vs. *Design 1*: *pairwise* analysis; $p > 0.05$, *Design 2* vs. *DMC* and *Design 1*: no overlap of 95%-confidence bands) (Table 4 and 5, Fig 6). As mentioned above, a 0.5 cm difference in mean L_{50} between the two similar *Design 2* codends was found to be significant (*pairwise* analysis; $p < 0.05$)(Table 5).

4. Discussion

We were able to estimate selection parameters for all three gear types, and both the standard diamond-mesh codend and the four-panel codends worked well and were easy to handle. The selection factor (SF = L_{50}/mesh size) often is used to validate the experimental setup by comparing SFs from other experiments using similar codends. In our study, we used the 90 mm standard diamond-mesh codend for this purpose. For all species, the SF was within the range reported in previous studies in the area (cod, 1.60–2.45; *Nephrops*, 0.18–0.38; plaice, 2.03–2.28 (Frandsen et al., 2009; Frandsen et al., 2010b; Madsen and Stæhr, 2005)).

Results from Exp 1 indicated that the new codend concept succeed in improving the size selectivity of *Nephrops* with no increase in discards of cod and plaice. Overall, for *Nephrops* and cod, estimated L_{50} and SR/L_{50} of *Design 1* were comparable to these of a full square-mesh codend made of the same netting as the panel (L_{50}: cod, 26.3–26.9 cm; *Nephrops*, 31.0–41.2 mm (Frandsen et al., 2010b)) and significantly improved compared to the *DMC*. Size selectivity of plaice in *Design 1*, on the other hand, did not differ significantly from that of the *DMC* but it was improved compared to that of a full square-mesh codend (Frandsen et al., 2010b). This indicates that different nettings can be combined to simultaneously optimize size selectivity of morphologically different species.

However, the size selectivity for *Nephrops* in *Design 1* was not adjusted to the MLS and compared to the *DMC*, its use would result in a > 20% increase in expected loss of legal-sized *Nephrops* if fished on the size distributions found in these experiments. Insertion of the new type of square-mesh netting in *Design 2* was expected to result in a reduction in L_{50} for *Nephrops* as the mesh size of the square-mesh netting was reduced and the twine thickness was increased. Both factors are expected to decrease the selectivity of the panel but the setup of the experiment did not allow a quantification of the effect of the two factors isolated. Besides differences in the netting material of the square-mesh panel, season, depth, size structure of the fished populations, haul duration, and catch size differed between Exp 1 and Exp 2. All these factors may also affect size selectivity of the codends and even though the experiments were conducted using the same vessel, the same trawls and the same methodology, the differences preclude a global analysis including all three types of codend. The 95 % confidence bands of the selectivity estimates for *Design 2* are found to overlap with those of *Design 1* but the mean estimates indicate that a change of square-mesh panel can be used to adjust size selectivity of *Nephrops*.

If oriented optimally, maximum CL for *Nephrops* that can escape through a 70 mm square mesh is around 55 mm (based on information given in Frandsen et al., 2010a). Because the L_{50} of *Nephrops* for *Design 1* was estimated to be considerably lower (34.6 mm) than this, it is likely that many of the *Nephrops* were not oriented optimally when meeting the netting or did not meet the netting at all. Without further changes in the mesh size, the L_{50} of this species is expected to be considerably increased if contact with the netting is optimized. The *SR* estimate for *Nephrops* was slightly higher in *Design 1* than in a plain square-mesh codend (14.7–17.9 mm (Frandsen et al., 2010b)). This may further indicate that the selective potential for this species is not fully met in the five meter bottom panel which may be a consequence of the four-panel construction, which limits the width of the square-mesh bottom panel. Furthermore, the panel is 1 m shorter than the full square-mesh codend (6 m) investigated by Frandsen et al. (2010b). As *Nephrops* are likely to escape over the entire length of the codend (Frandsen et al., 2010a), this difference in panel length may influence the selectivity of the gear.

Our evaluations of the expected discards and losses are relevant for locations where the size structures of the species are similar to those found in our study. In other areas (e.g., deeper waters in the North Sea) where juveniles are few in number, the catches will most likely be very different for all gears. However, despite these limitations, the changes in expected landings and discards detected in our study are useful parameters for evaluating the effects of gear changes.

The *pairwise* analysis proved to be good at clearing the data of haul-specific variations, and thus it detected differences in selection parameters with a higher level of significance than the standard method. Traditionally, the experimental design with covers on both trawls in a twin trawl setup has been used simply to increase the number of hauls (Wileman et al., 1996). The *pairwise* method developed in this study further exploits the advantages of this setup, and the increased analytical power may allow a reduction in the number of tows required for analysis.

The results indicate that composite codends with square meshes in the lower panel of a four-panel codend may be used as a simple and flexible method to improve selectivity of *Nephrops* without negatively affecting discards of either plaice or cod. It is likely that some cod escape through the square-mesh panel, but the improved size selectivity of cod in *Design 1* compared to the *DMC* may also be partly explained by the four-panel construction, in which the four selvedges likely act as lastridge ropes on the codend and provide a higher initial opening of the meshes. Additional selective devices can be combined in this codend concept e.g. to mitigate the insufficient size selectivity of cod in the standard diamond-mesh netting. Previous studies have shown that large mesh (300 mm) square-mesh panels in the upper panel of a four-panel construction can significantly reduce discard of cod (Madsen et al., 2010). Such a panel can be inserted in the codend concept tested here. With regards to the size selectivity of *Nephrops*, ways to further improve this through an increase in the contact between *Nephrops* and the panel should be explored. An extension and/or inclination of the panel could increase the number of contacts between *Nephrops* and the netting and if these measures prove to be successful, further adjustments regarding the selective properties of the square-mesh netting may be needed.

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Table 1.Operational conditions for the cruises given as mean values and standard deviation (sd).

Table 2. Catches in numbers in all hauls and compartments and total catch in weight in the test codend. Bold numbers indicate that the fraction was subsampled and the numbers have been raised.

Table 3. Selection parameters and fit statistics on haul level (Degrees of freedom: DOF). The two gears tested on the same cruise are referred to as A and B. This denotion remains in the haul ID.

Table 4. Selection parameter estimates for all three gears. Estimates for *Nephrops* are in mm. The estimated between haul variation is represented by the D-matrix (see section 3.1).

Table 5. Differences in selection parameter estimates (ΔL_{50} and ΔSR) between gears towed parallel estimated in the *pairwise* analysis.

Table 6. Expected catch rate in the standard codend (*DMC*) and the four-panel codends (*Design 1* and *Design 2*). The expected catches are based on length distributions in Exp 1 and Exp 2 respectively. Expected catch rates below MLS (discard) are based on numbers whereas those above MLS (landings) are based on weight (see section 2.5.2). MLS: cod = 30 cm, *Nephrops* = 40 mm, plaice = 27 cm.

Table 1.

	Exp 1		Exp 2	
	mean	sd	mean	sd
Haul duration (h:mm)	3:56	0:25	3:07	0:08
Windspeed (m/s)	7.6	2.2	7.4	3.0
Speed (knot)	2.7	0.2	2.7	0.3
Depth (m)	53.8	16.6	30.8	5.6
Wire length (m)	245.5	37.7	238.4	0.0
Door dist. (m)	101.2	2.1	101.6	1.9

Table 2.

		DMC							*Design 1*						
		Cod		*Nephrops*		Plaice		Total catch in test (kg)	Cod		*Nephrops*		Plaice		Total catch in test (kg)
	Haul no	Cover	Test	Cover	Test	Cover	Test		Cover	Test	Cover	Test	Cover	Test	
Exp 1	1	59	189	**141**	**1962**	12	209	448	91	112	**523**	**713**	11	202	403
	2	76	161	358	**2998**	52	142	376	177	57	**1025**	**2375**	34	153	395
	3	53	234	72	**1316**	25	178	492	134	66	450	**1040**	35	131	282
	4	54	101	**850**	**4509**	31	107	400	123	56	**1536**	**3923**	40	101	330
	5	72	141	323	**625**	41	135	310	130	40	737	**456**	62	103	140
	6	91	100	150	**564**	28	81	250	157	45	321	**268**	46	66	170
	7	48	62	84	228	32	88	230	74	27	190	85	34	82	110
	8	43	71	**674**	**560**	54	81	220	65	25	**1096**	**545**	25	91	160
	9	69	257	14	16	46	225	375	95	178	22	16	35	207	270
	10	23	75	15	143	25	72	210	28	52	78	111	38	66	170
	11	10	50	62	211	52	41	160	64	27	159	83	41	63	80
	12	10	61	107	618	36	117	250	59	21	453	352	59	89	100
	13	50	93	115	884	78	96	240	42	67	382	628	62	94	290
	14	9	191	4	77	0	6	1020	17	140	42	54	0	4	570
		Design 2							*Design 2*						
Exp 2	21	40	8	**1664**	**1670**	377	60	185	65	12	**1363**	**2507**	404	77	270
	22	79	10	**942**	**464**	191	53	248	161	12	**878**	**760**	281	71	158
	23	79	12	**1182**	**3176**	619	77	225	137	8	**1249**	**3928**	504	78	275
	24	108	4	**913**	**2126**	288	64	n.a.	254	11	**1032**	**2242**	406	78	215
	25	27	5	**1206**	**2727**	419	67	220	66	10	**1458**	**3424**	530	90	270

Table 3.

Gear	Haul ID	Cod L_{50}	Cod SR	Cod P-Value	Cod Deviance	Cod DOF	Cod r^2-Value	*Nephrops* L_{50}	*Nephrops* SR	*Nephrops* P-Value	*Nephrops* Deviance	*Nephrops* DOF	*Nephrops* r^2-Value	Plaice L_{50}	Plaice SR	Plaice P-Value	Plaice Deviance	Plaice DOF	Plaice r^2-Value
DMC	1A	11.38	23.04	0.67	22.38	26	0.29	2.10	28.52	0.99	16.12	32	0.43	16.57	5.94	0.64	20.04	23	-0.01
	2A	19.68	13.68	1.00	13.03	31	0.61	9.81	24.65	0.01	50.47	28	0.41	21.41	2.03	0.99	7.92	19	0.97
	3A	16.10	11.23	0.62	28.91	32	0.05	13.82	15.87	0.02	43.65	27	0.63	19.39	3.48	0.99	8.02	20	0.87
	4A	22.33	6.17	1.00	13.08	29	0.91	22.33	14.10	0.56	26.30	28	0.85	20.90	1.61	1.00	4.21	17	0.99
	5A	21.90	5.18	0.89	18.38	27	0.69	29.75	21.68	0.70	27.36	32	0.54	21.71	2.61	0.83	14.10	20	0.89
	6A	24.24	11.11	0.70	21.77	26	0.73	24.84	17.29	0.26	35.53	31	0.72	22.06	1.30	1.00	2.91	15	0.99
	7A	22.10	16.80	0.32	20.18	18	0.34	25.51	18.97	0.86	21.09	29	0.51	22.14	1.90	0.88	12.08	19	0.94
	8A	20.69	12.16	0.17	24.63	19	0.23	35.72	14.87	0.74	24.70	30	0.87	22.54	1.93	1.00	3.88	16	0.99
	9A	26.77	6.89	1.00	16.98	51	0.96	42.75	14.45	0.34	18.79	17	0.45	21.82	2.51	0.94	14.90	25	0.96
	10A	0.10	45.26	0.19	23.13	18	-0.06	17.15	13.82	0.53	22.75	24	0.20	17.59	8.05	0.28	17.71	15	0.08
	11A	18.07	5.50	0.94	9.13	17	0.58	27.70	10.44	0.81	24.10	31	0.62	22.17	1.66	0.99	5.78	17	0.99
	12A	5.23	22.06	0.63	13.54	16	0.07	22.67	13.28	0.33	31.80	29	0.47	19.28	3.59	0.99	7.84	19	0.94
	13A	20.75	9.00	0.67	15.85	19	-0.03	18.23	16.36	0.72	25.98	31	0.48	21.93	2.05	0.64	12.48	15	0.98
	14A	5.31	20.01	1.00	16.42	56	0.10	16.79	13.03	0.81	18.80	25	0.24	0.10	0.10	1.00	0.00	2	0.00
Design 1	1B	22.85	6.04	0.99	16.32	32	0.62	34.00	13.93	0.73	16.64	21	0.49	20.49	2.50	1.00	5.79	20	0.95
	2B	28.26	4.24	1.00	11.27	28	0.97	36.80	15.00	0.22	35.55	30	0.83	21.73	2.04	0.83	9.87	15	0.99
	3B	26.97	5.36	0.97	13.92	26	0.95	25.76	23.04	0.94	15.86	26	0.75	21.61	1.92	0.99	6.76	18	0.98
	4B	26.94	5.03	1.00	8.67	27	0.98	22.83	35.66	0.16	38.63	31	-0.02	22.23	2.33	0.45	19.06	19	0.97
	5B	28.70	5.60	0.01	45.19	25	0.67	21.61	28.22	0.01	51.31	29	0.32	22.46	3.88	0.37	20.42	19	0.95
	6B	28.04	4.74	0.82	15.12	21	0.94	37.59	33.87	0.02	48.03	30	0.19	22.63	1.15	1.00	1.60	15	1.00
	7B	27.21	6.38	0.51	18.25	19	0.60	39.01	29.13	0.89	20.15	29	0.67	22.52	2.65	0.79	12.23	17	0.95
	8B	27.90	6.80	0.72	15.05	19	0.84	58.47	62.21	0.01	49.65	30	0.15	22.05	1.48	0.99	3.66	13	0.99
	9B	28.39	6.22	0.40	44.75	43	0.90	44.29	32.01	0.28	34.1	30	0.33	21.85	2.03	0.55	19.58	21	0.98
	10B	19.98	8.13	0.19	17.30	13	0.52	48.34	53.94	0.15	25.23	19	0.01	20.17	2.34	1.00	6.29	20	0.97
	11B	26.45	4.98	0.99	7.90	19	0.91	30.23	12.76	0.93	17.16	27	0.68	20.68	2.00	1.00	2.79	14	0.99
	12B	28.12	5.67	0.76	13.47	18	0.78	41.99	21.05	0.34	30.49	28	0.33	22.02	2.34	0.50	13.29	14	0.96
	13B	21.91	9.69	0.91	10.49	18	0.52	36.82	19.83	0.31	36.48	33	0.83	21.40	2.27	0.56	15.48	17	0.96
	14B	23.30	4.69	1.00	8.99	52	0.51	29.73	21.43	0.62	29.86	33	0.78	0.10	0.10	1.00	0.00	1.00	0.00
Design 2	21A	22.68	6.26	0.63	9.87	12	0.67	34.19	23.95	0.53	28.72	30	0.20	22.95	2.45	0.00	50.83	20	0.48
	22A	24.50	0.10	1.00	0.00	13	1.00	38.21	13.24	0.39	32.50	31	0.87	22.21	3.19	0.85	12.77	19	0.97
	23A	16.21	1.98	1.00	3.45	14	0.96	24.57	19.02	0.00	57.57	29	0.05	22.32	1.88	0.99	8.85	21	1.00
	24A	27.02	4.03	0.91	4.78	10	0.54	22.74	25.54	0.14	40.81	32	0.46	22.85	2.07	0.96	11.31	21	0.99
	25A	25.10	3.90	0.72	7.09	10	0.55	27.13	16.32	0.49	29.62	30	0.88	22.44	2.30	0.33	23.23	21	0.99
	21B	25.41	4.08	0.96	7.64	16	0.84	34.91	15.32	0.39	28.47	27	0.40	22.32	2.82	0.98	10.15	21	0.99
	22B	16.57	1.54	1.00	1.72	13	0.99	34.14	14.52	0.37	29.91	28	0.90	21.33	2.40	0.42	17.50	17	0.99
	23B	20.43	3.76	0.98	3.76	11	1.00	22.58	20.33	0.00	53.15	29	0.34	22.45	2.56	0.87	14.88	22	0.99
	24B	24.60	5.44	0.86	8.61	14	0.80	24.99	21.05	0.58	27.87	30	0.57	22.04	2.22	0.50	20.28	21	0.99
	25B	25.34	0.10	1.00	0.00	11	1.00	28.97	11.55	0.91	19.27	29	0.96	21.80	2.14	0.99	10.77	23	1.00

Table 4.

		DMC			*Design 1*			*Design 2*		
		Cod	*Nephrops*	Plaice	Cod	*Nephrops*	Plaice	Cod	*Nephrops*	Plaice
L_{50}	Mean estimate (cm)	21.43	23.99	21.22	26.10	34.58	21.72	22.52	29.54	22.20
	Standard error (cm)	0.78	2.19	0.33	0.70	1.56	0.21	1.28	1.72	0.15
	95% confidence limits (cm)	19.74-23.10	19.26-28.72	20.49-21.95	24.58-27.62	31.22-37.94	21.26-22.19	19.58-25.47	25.64-33.43	21.87-22.54
	P-value for value different from 0.0	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	95% limits for between haul variation (cm)	16.64-26.20	8.76-39.22	19.05-23.40	21.15-31.05	23.95-45.22	20.35-23.10	15.64-29.41	19.06-40.02	21.47-22.94
SR	Mean estimate (cm)	6.96	14.67	2.30	5.29	19.58	2.10	4.34	16.81	2.31
	Standard error (cm)	0.66	0.88	0.23	0.30	1.55	0.16	0.59	1.34	0.11
	95% confidence limits (cm)	5.52-8.40	12.76-16.57	1.80-2.80	4.65-5.94	16.23-22.93	1.76-2.45	2.97-5.71	13.79-19.83	2.07-2.55
	P-value for value different from 0.0	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	95% limits for between haul variation (cm)	4.99-8.93	11.94-17.39	1.00-3.60	4.92-5.67	12.98-26.18	1.33-2.87	1.73-6.95	9.94-23.68	1.99- 2.63
SF	L50/mesh size converted to the EU wedge	2.25	0.25	2.22						
SR/L_{50}	Relative steepness of selection curve	0.32	0.61	0.11	0.20	0.57	0.10	0.19	0.57	0.10
D-matrix	D11 (cm2)	5.94	60.37	1.23	6.38	29.43	0.49	12.33	28.61	0.14
	D12 (cm2)	-0.04	-1.87	-0.66	-0.48	6.08	-0.06	4.67	-11.25	-0.04
	D22 (cm2)	100.57	1.93	0.44	0.04	11.33	0.15	1.77	12.28	0.03
Model	Log likelihood value	-133.56	-143.02	-87.75	-111.07	-150.36	-80.14	-74.83	-94.31	-50.96
	AIC value	277	296	186	232	311	170	160	199	112
Data	Number of hauls	14	14	13	14	14	13	9	10	10
Fixed effects	P-value for significance of catch on L50	0.491	0.116	0.071	0.207	0.062	0.614	0.325	0.595	0.412
	P-value for significance of catch on SR	0.493	0.428	0.253	0.443	0.270	0.884	0.448	0.423	0.544

Table 5.

		DMC → Design 1			*Design 2 → Design 2*		
		Cod	*Nephrops*	Plaice	Cod	*Nephrops*	Plaice
ΔL_{50}	Mean estimate (cm)	5.03	11.39	0.55	1.81	0.15	-0.56
	Standard error (cm)	0.72	1.36	0.33	2.13	1.32	0.21
	95% confidence limits (cm)	3.48-6.58	8.46-14.31	-0.18-1.28	-7.34-10.96	-3.50-3.81	-1.16-0.03
	P-value for value different from 0.0	<0.0001	<0.0001	0.1131	0.4844	0.9115	0.0384
ΔSR	Mean estimate (cm)	-2.04	7.14	-0.25	0.48	-3.23	0.03
	Standard error (cm)	0.66	1.86	0.23	1.25	1.92	0.28
	95% confidence limits (cm)	-3.46- -0.62	3.12-11.16	-0.75-0.25	-4.92-5.88	-8.57-2.12	-0.74-0.80
	P-value for value different from 0.0	0.0049	0.0008	0.2805	0.7390	0.1445	0.9200
Data	Number of twin hauls	14	14	13	3	5	5

Table 6.

		Exp 1			Exp 2		
		DMC	*Design 1*	*Design 2*	*DMC*	*Design 1*	*Design 2*
Cod	Below MLS (no.)	0.62	0.31	0.58	0.11	0.04	0.07
	Above MLS (kg)	0.98	0.97	0.98	0.98	0.95	0.98
Nephrops	Below MLS (no.)	0.74	0.47	0.59	0.72	0.45	0.57
	Above MLS (kg)	0.92	0.73	0.85	0.91	0.71	0.84
Plaice	Below MLS (no.)	0.66	0.63	0.57	0.18	0.15	0.13
	Above MLS (kg)	1.00	1.00	1.00	1.00	1.00	1.00

Fig 1. *Design 1* tested in the Hirtshals flumetank.

Fig 2. Codends tested in the two cruises. Mesh openings (M.o.) are means (± 2S.E.)

Fig 3. Distribution of hauls in Cruise 1 and Cruise 2.

Fig 4. Length distributions based on raised catches in codends + covers in cruise 1 (dotted line) and cruise 2 (broken line). MLS is indicated as vertical lines. Lengths refers to total length for fish and CL for *Nephrops*.

Fig 5. L_{50} on haul level for gear A (black circles) and gear B (white circles). Haul number refers to the haul number given in table 2. In haul 1-14 gear A and gear B is the *DMC* and *Design 1* respectively. In haul 21-25 gear A and gear B are two codends of similar design (*Design 2*).

Fig 6. Mean selection curves with 95% confidence range for the *DMC* (vertical lines), *Design 1* (horizontal lines), and *Design 2* (pale gray)

Fig. 1

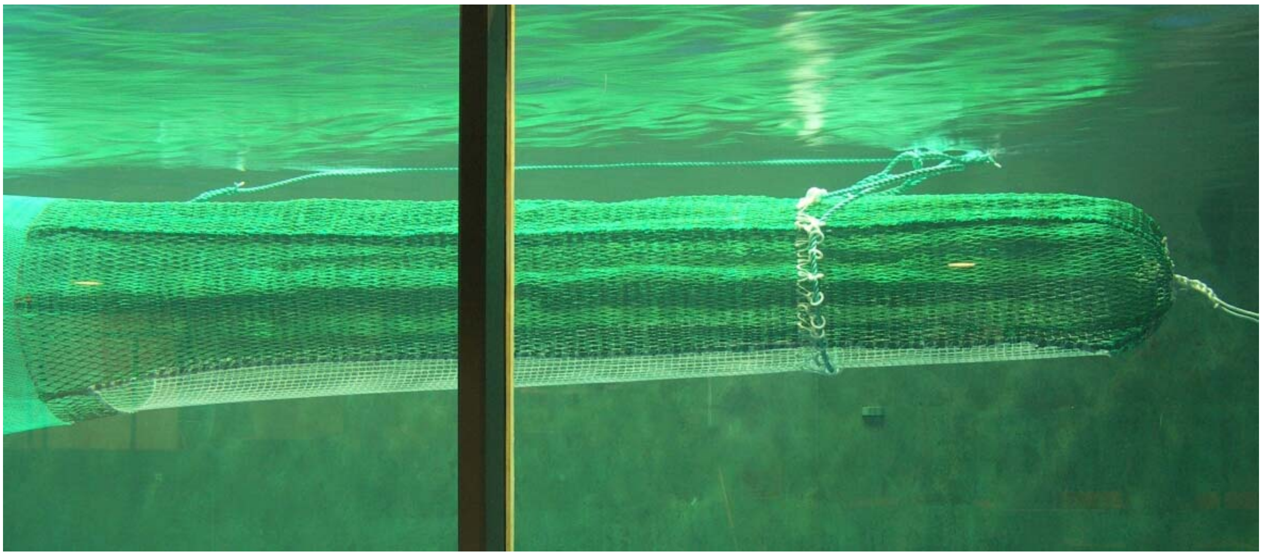


Fig 2.

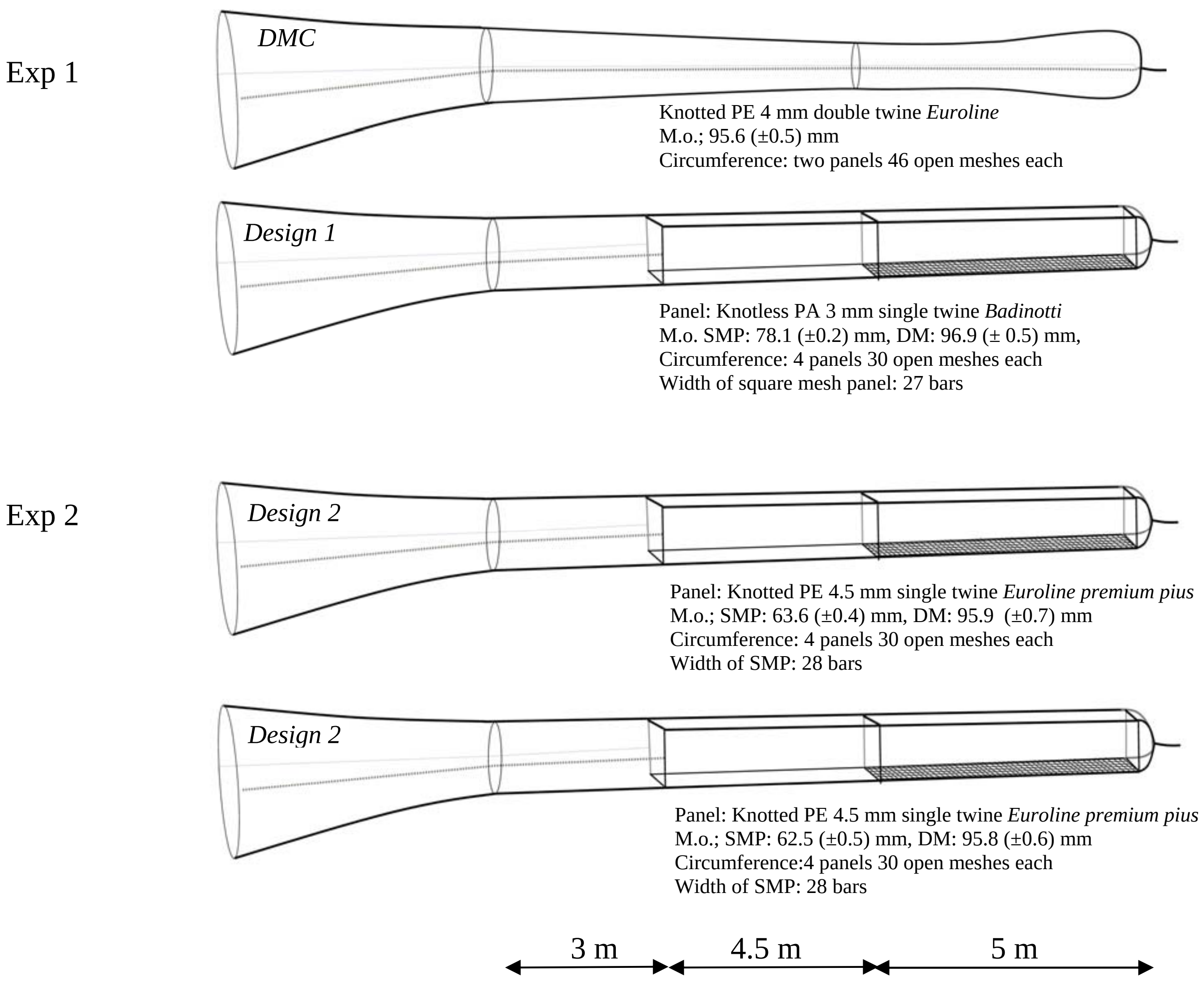

Exp 1
DMC
Knotted PE 4 mm double twine *Euroline*
M.o.; 95.6 (±0.5) mm
Circumference: two panels 46 open meshes each
Design 1
Panel: Knotless PA 3 mm single twine *Badinotti*
M.o. SMP: 78.1 (±0.2) mm, DM: 96.9 (± 0.5) mm,
Circumference: 4 panels 30 open meshes each
Width of square mesh panel: 27 bars
Exp 2
Design 2
Panel: Knotted PE 4.5 mm single twine *Euroline premium pius*
M.o.; SMP: 63.6 (±0.4) mm, DM: 95.9 (±0.7) mm
Circumference: 4 panels 30 open meshes each
Width of SMP: 28 bars
Design 2
Panel: Knotted PE 4.5 mm single twine *Euroline premium pius*
M.o.; SMP: 62.5 (±0.5) mm, DM: 95.8 (±0.6) mm
Circumference:4 panels 30 open meshes each
Width of SMP: 28 bars
3 m
4.5 m
5 m

Fig. 3

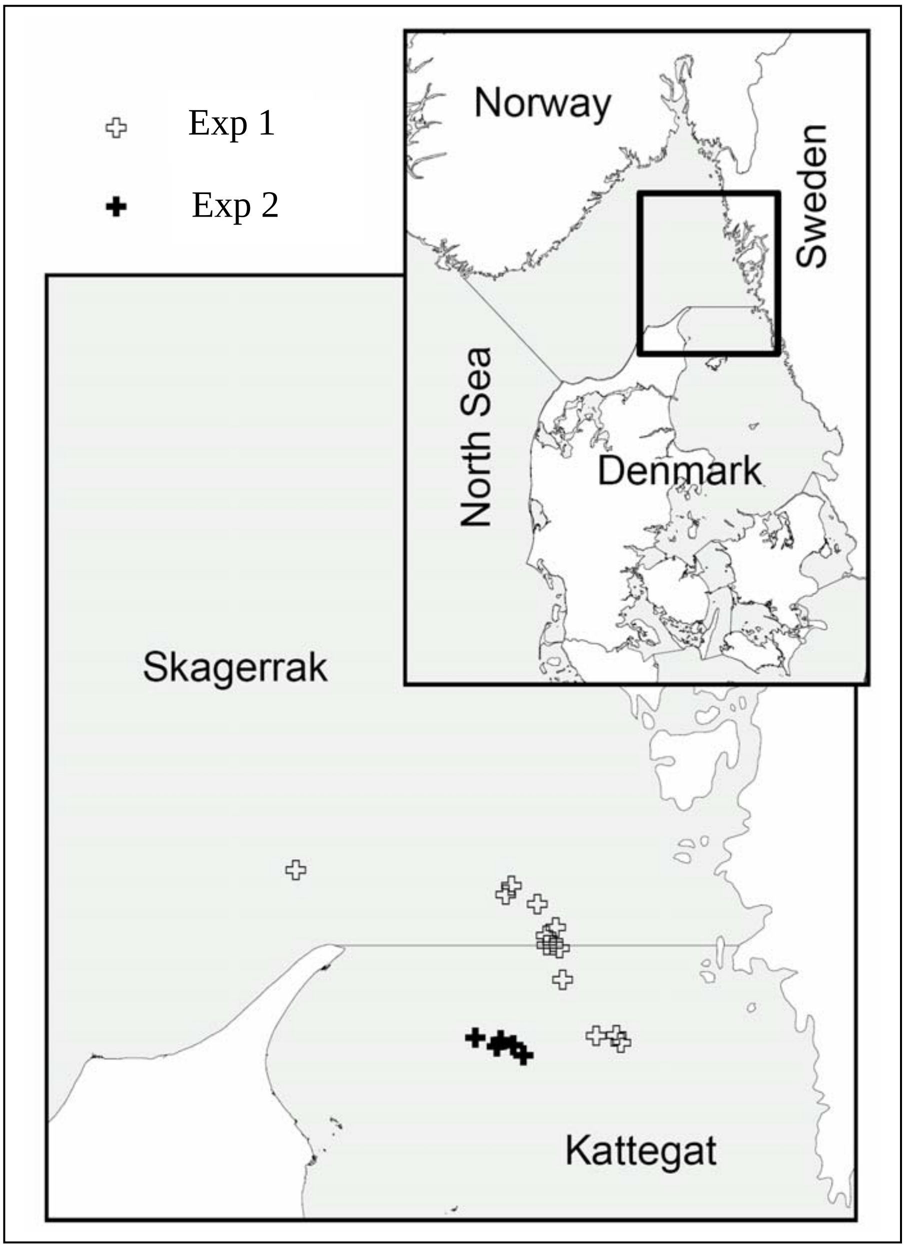
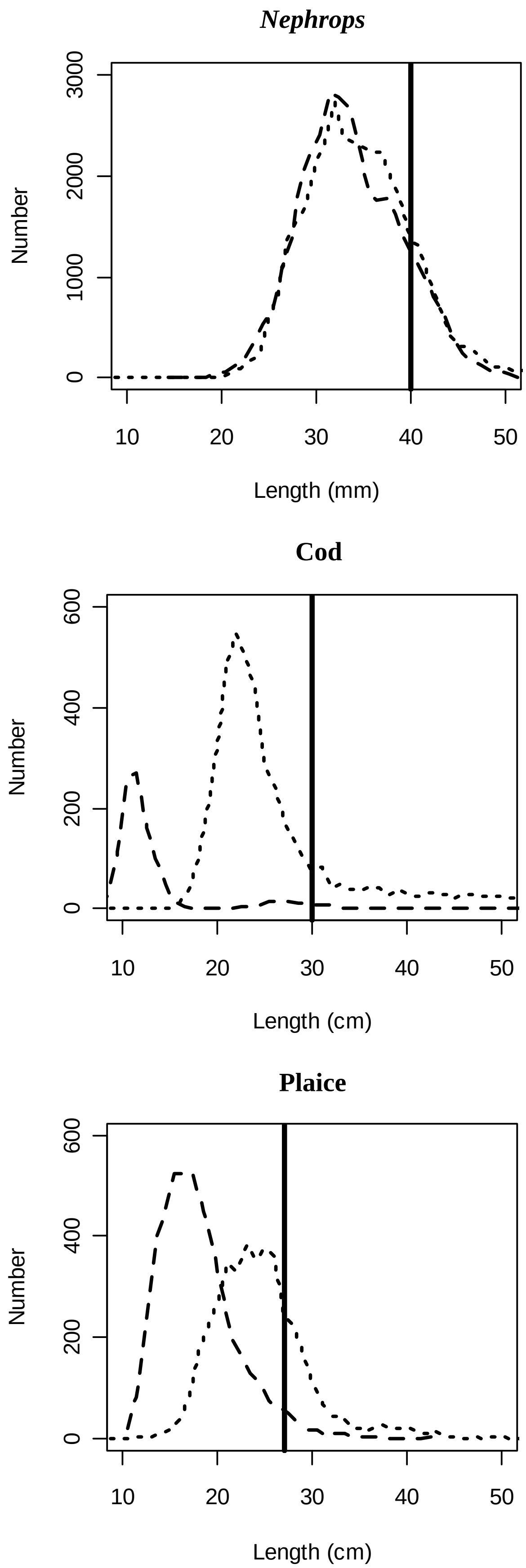

Exp 1
Exp 2
Norway
Sweden
North Sea
Denmark
Skagerrak
Kattegat

Fig 4.



Nephrops
Number
0
1000
2000
3000
10
20
30
40
50
Length (mm)
Cod
Number
0
200
400
600
10
20
30
40
50
Length (cm)
Plaice
Number
0
200
400
600
10
20
30
40
50
Length (cm)

Fig 5.

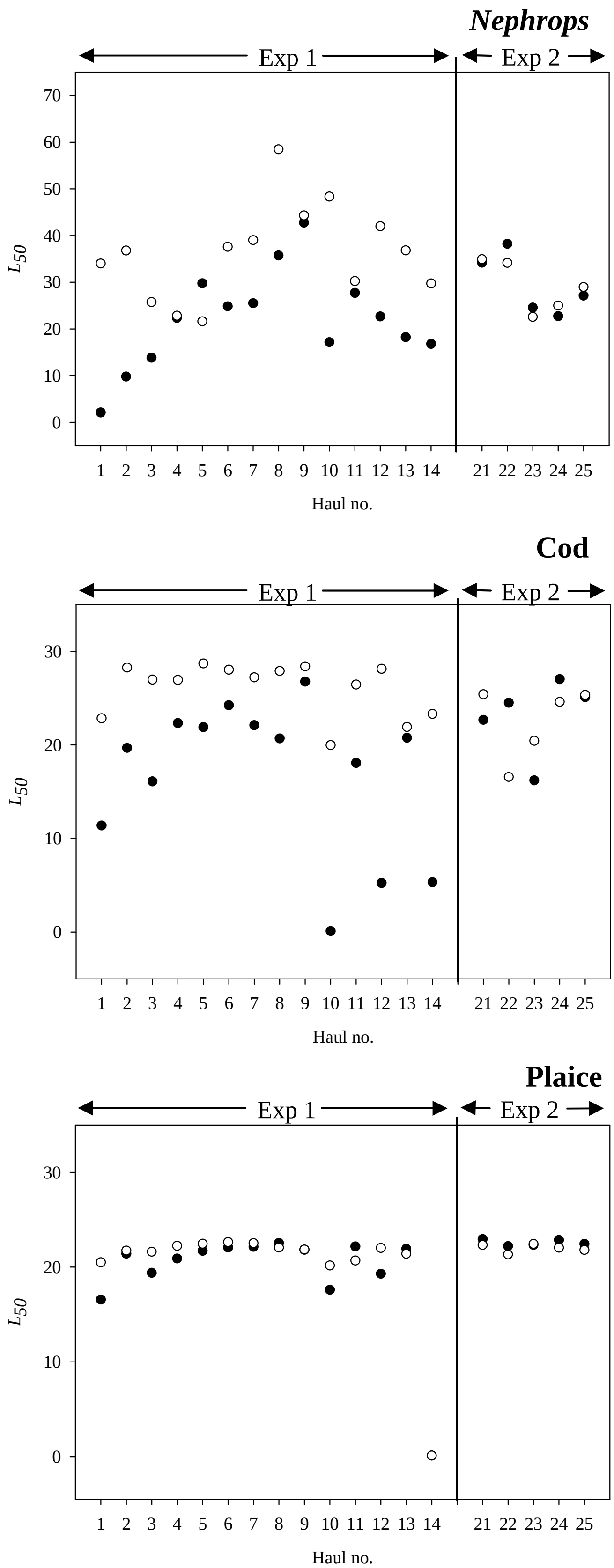
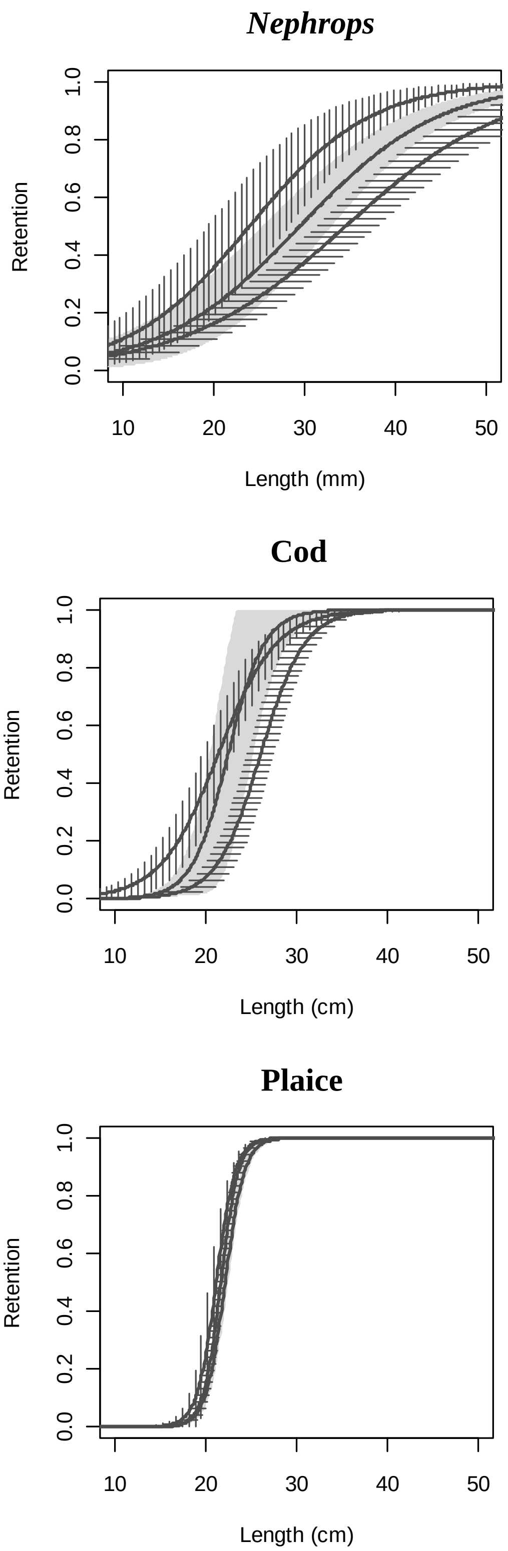

Nephrops
Exp 1
Exp 2
70
60
50
40
30
20
10
0
L_{50}
1 2 3 4 5 6 7 8 9 10 11 12 13 14 21 22 23 24 25
Haul no.
Cod
Exp 1
Exp 2
30
20
10
0
L_{50}
1 2 3 4 5 6 7 8 9 10 11 12 13 14 21 22 23 24 25
Haul no.
Plaice
Exp 1
Exp 2
30
20
10
0
L_{50}
1 2 3 4 5 6 7 8 9 10 11 12 13 14 21 22 23 24 25
Haul no.

Fig 6.


Nephrops
Retention
1.0
0.8
0.6
0.4
0.2
0.0
10
20
30
40
50
Length (mm)
Cod
Retention
Length (cm)
Plaice
Retention
Length (cm)